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THE UPLAND DIAMOND DEPOSITS OF THE DIAMANTINA DISTRICT, MINAS GERAES, BRAZIL.

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INTRODUCTION.

THE overwhelmingly large output of diamonds in South Africa has so eclipsed the production of other countries that one is apt to forget the part played in the world's gem trade by smaller pro-

ducers. This applies especially to Brazil. Here, with the impetus given diamond mining in South Africa by the discovery of the pipes at Kimberley, this industry shrank to insignificant proportions, both relatively and in respect to total production. Yet this country was for a long time the world's chief producer and

FIG. 1. Sketch map of the Diamantina District showing location of principal upland deposits.

for many years enjoyed almost a monopoly. The occurrences of diamonds in this South American republic, however, are so widespread, and the total amount of work done has been so very small, that it is conceivable that the country may again rise to a position of great importance in the diamond industry.

The oldest and most important diamond field of Brazil, thus far discovered, is that of Diamantina, in the State of Minas Geraes. (Fig. 1.) The diamondiferous area extends from a short distance south of the town of Dattas to a point about 150 kilometers to the north, where it joins the district of Grão Mogul. No diamonds have been found east of the Jequitinhonha River, and the western limit of known occurrences is a line roughly parallel to that stream and about 50 kilometers from it. The

FIG. 2. The City of Diamantina from the north.

commercial center of this region is Diamantina (Fig. 2), a city of about 12,000 inhabitants, which is situated at latitude 18° 16′ south and longitude 43°. This places it almost due north of Rio de Janeiro and about 600 kilometers from that city in an air line. Diamantina is the eastern terminus of a branch of the uncompleted Victoria and Minas Railway, which connects at Curralinho with the Estrada de Ferro Central do Brazil. The total distance by rail from Rio de Janeiro is 902 kilometers. The journey requires a day and a half.

This area has been visited by several geologists during the past century, and a considerable volume of literature on the district has been published. Developments of later date than the bulk of this work, and some new discoveries have, however, served

to emphasize the importance of a most interesting type of diamond deposit, namely, the occurrences in the breccias, the nature of which sheds much light on the origin of the diamonds.

Surface Features.—The Diamantina district occupies the height of land known as the Serra do Espinhaço which forms the divide between the drainage basins of the São Francisco and Jequitinhonha Rivers. East of the Jequitinhonha, the country is rugged; but the diamond district proper is characterized more by "inselberg" topography,—isolated, rocky peaks rising to

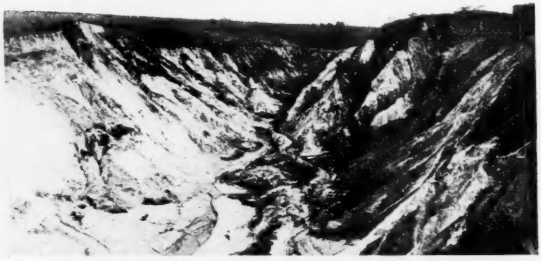

FIG. 3. The great open cut at São João da Chapada, and the uplands, looking north.

heights of 200 or 300 meters above a broad, rolling plain. The altitude of the plain itself is between 1,100 and 1,500 meters above sea level. Many small streams and a few important rivers rise in the area. The valleys vary from gentle depressions to steep-sided canyons which, in the case of the larger rivers, are cut to depths of as much as 300 or 400 meters below the level of the surrounding country.

The general aspect of the region is one of desolation. The rocky peaks are utterly bare, and the intervening plains are covered only with sparse, short grass (Fig. 3). Bushes and trees are rarely ever seen away from the stream courses, and there, as a rule, only small, stunted varieties are found. In the lower val-

leys of the larger rivers, there are, however, good stands of hard wood.

The climate is healthy. The temperature is rarely ever higher than 25 deg. C., even on the hottest days. The nights are always cool, and frost has been reported in the district at rare intervals. The rainfall is never excessive, avering little over 1,000 millimeters a year. It usually occurs in small showers during the period from September to May. The remaining months are quite dry.

GENERAL GEOLOGY.

The part of eastern Brazil which includes the diamond areas is, in general, a region which has apparently been a land area since remote time. The Diamantina district especially has been subjected to a long period of erosion. Here most of even the more ancient sediments found elsewhere in Minas Geraes have been removed, so that only two geological formations of any extent are found in the district.

The Basement Complex.—The oldest rocks exposed in the vicinity of Diamantina are crystalline schists. In some places, these are found interbedded with layers of quartzite. Weathering has progressed to great depths,—often 100 meters or more,—yielding a stiff, red clay. Quartz stringers are abundant throughout much of this formation.

The basement complex is separated from the rocks immediately overlying it by a marked unconformity.

The Caraça Quartzite.—This formation is all that remains locally of a thick series of sediments, probably of Algonkian age, which is found well developed in other parts of Minas Geraes. This series, of which the Caraça quartzite is the basal formation, has been described in detail by Harder and Chamberlin.[1] These quartzites cover the greater part of the area.

At, or very near, the base of the Caraça quartzite is a rather persistent bed of conglomerate. This bed is easily traced from a point five kilometers south of Dattas to some distance north of

[1] Harder, E. C., and Chamberlin, R. T., "The Geology of Central Minas Geraes, Brazil," *Jour. Geol.*, vol. 23, pp. 341–378; 385–424, 1915.

Sopa, and further studies may reveal its extent far beyond these limits. Folding and faulting have duplicated the outcrop of this conglomerate to either side of the main line of exposure in several places.

At Sopa and Guinda, the conglomerate lies directly on the schists of the basement complex. Near Dattas, however, it is separated from the older formation by 100 meters or more of a coarse-grained, metamorphosed sandstone which is not distinguishable lithologically from the coarse quartzites above it.

In no exposure seen is this conglomerate less than ten meters thick, and in some places, as much as 25 meters were noted. Most of the pebbles are well rounded and even the more angular forms show unmistakable signs of wear. On the whole, they are not well sorted. Some large boulders occur, but the average size of the pebbles is 15 centimeters or less in their greatest dimension. The pebbles present a wide range of composition. Different varieties of quartz and quartzite are most abundant, but many, which are represented in the weathered exposures by clayey masses, were probably derived from igneous or older metamorphic rocks. The matrix is medium-grained quartz sand, sometimes slightly argillaceous or micaceous, and frequently stained with iron oxide. Secondary silicification appears to have played an important part in the consolidation of the rock. On the whole, the conglomerate weathers somewhat more rapidly than the quartzite proper, the speed of disintegration varying with the quantity of clay, mica or iron oxide present in the matrix.

Immediately above the conglomerate is a thickness of at least 40 meters of very coarse, cross-bedded sandstone which is overlain by roughly 1,000 meters of fine grained, gray quartzite, usually more or less schistose. In several places, thin, micaceous layers were seen, which form a flexible sandstone similar to that found in the Itacolumi quartzite which occurs higher in the series in other parts of the state.

Period of Uplift and Erosion.—Owing to the lack of a complete stratigraphic record, it is impossible to fix the time of geologic events with any degree of accuracy. At a time, pre-

sumably not later than middle Paleozoic, a great mountain-making uplift took place. This was followed by a long period of erosion lasting possibly until late Tertiary which resulted in the peneplanation of the entire region.

The Diamantina Conglomerate.—Isolated patches of poorly sorted conglomerate, with which are sometimes associated beds of fine sands and silts, occur at various points in the district. The conglomerate, which is usually fairly well consolidated, is composed chiefly of angular to subangular fragments of vein quartz and pebbles of quartzite in a matrix of fine sand and silt, often somewhat argillaceous. These occurrences evidently represent remnants of more extensive deposits which were laid down on the old peneplain. There is no definite clue to their age, but from the general history of eastern Brazil, the deposits are most probably either late Tertiary or Pleistocene. This formation completes the geologic column on the uplands.

Metamorphism.—Regional metamorphism has affected both the Caraça quartzite and the rocks of the basement complex. Although there is no conclusive evidence, it is possible that the older rocks were extensively metamorphosed before the deposition of the quartzites, and that the processes were continued during the great movements in which the later formation was involved.

From the field examination, it seems most likely that the Caraça quartzite was indurated by secondary silicification at some time prior to its deformation. The cleavage planes and schistosity were developed later, during the mountain-making uplift.

Igneous Rocks.

Basic Dikes.—Occurrences of rock in place to which an igneous origin can definitely be assigned are rare. At a few places, well defined dikes of decomposed material are to be seen cutting the country rock, often at steep angles to the bedding planes. The largest of these is a dike nearly twelve meters thick, cuts the body of breccia at Boa Vista. The material of this dike resembles a decomposed diabase.

Cutting the quartzite in the walls of the Barro-Duro open cut

at São João da Chapada are at least two thin dikes of thicknesses varying from 20 to 40 centimeters. The dike material is a talcy clay, very light bluish green to almost white in color. It is too much decomposed to afford direct clue to the original mineralogi-

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FIG. 4. Small dike cutting east wall of open cut at São João da Chapada. The wall rock is decomposed Caraça quartzite, the bedding planes of which are clearly shown in the small pinacle just above the upper end of the dike.

FIG. 5. Detail of the breccia at São João da Chapada.

cal composition. Crude qualitative tests indicate an abundance of magnesia. Some small flakes of a green micaceous mineral, probably chlorite, were seen in a few places.

Samples of the dike material were washed in a gold pan. After removing the bulk of the clay as slimes, a concentrate remained

in which the following minerals were identified: Rutile, anatase, ilmenite, kyanite, tourmaline, monazite, magnetite.

This list is so small that it affords very little, if any, conclusive evidence as to the original nature of the rock. Some of these minerals, especially the rutile, anatase, and possibly the tourmaline, are undoubtedly of secondary origin. The monazite, kyanite, and very likely the magnetite and ilmenite, are primary minerals. None of the mineral particles or crystals are rolled, but present a fresh, clear-cut appearance.

The mode of occurrence of the dikes, together with the scanty evidence afforded by the contained minerals, shows that the rock is of igneous origin. Monazite and kyanite are usually found only in deep seated granites or their metamorphic equivalents. The high percentage of magnesia indicated by the qualitative tests and the great abundance of iron and titanium minerals would suggest that the rock is basic rather than acid.

Derby [2] describes another rock found on the Grão Mogul road at a point several kilometers north of São João da Chapada, which may have a bearing on the case. It is of the appearance of an imperfectly laminated phyllite, full of enormous crystals of kyanite. The groundmass contains abundant chlorite. The rock is free from iron ores, but is extremely rich in minute aggregates of rutile and an extremely minute prismatic needle that is referred to monazite.

Breccias.—At several localities in the district, large bodies of breccia were seen. Important deposits of diamonds are found in these breccias, and they warrant detailed study. The occurrences are roughly elliptical in plan, with axes that reach several hundred meters in length. The depth of these deposits is unknown. Bore holes on the Barro-Duro property show that there is no change in the material to at least 60 meters beneath the surface, and at Boa Vista the proven depth is something over half this figure. In both places, there is indirect evidence that the deposits go much

[2] Derby, Orville A., "On the Association of Argillaceous Rocks with Quartz Veins in the Region of Diamantina, Brazil." *Am. Jour. Sci.*, 4th Ser., vol. 7, pp. 343–356, 1899.

deeper. In all the occurrences visited, the wall rock is Caraça quartzite. The contact is sharply defined. In some instances, a bulging of the beds near the contact is indicated by sharply increased dips. This is, however, not a universal characteristic.

Lithologically, there is but little difference between the breccias of the various localities, the most noticeable variation being in the relative abundance of the boulders. Fragments of Caraça

FIG. 6. Detail of the breccia at São João da Chapada. The size of the fragments is shown by the ordinary match box just to the right of the center.

quartzite are abundant and are the most readily recognized of any of the constituents. Pieces of schist were noted, together with fragments of other rocks not found in any known exposures in the area. In no case, do the fragments show any differences in the hand specimens from the parent rock wherever the source can be identified. The few water-worn boulders found in the mass of material have undoubtedly been derived from old conglomerates. Many boulders are marked with cavities suggestive of solution embayments. Frequently boulders are shattered, and the cracks filled with the matrix material. The arrangement of the fragments in the breccia is very striking. The long dimensions are roughly parallel, and usually stand either vertically or at

steep angles regardless of the attitude of the beds of the wall rock. These features are well illustrated in the accompanying photographs.

In the hand specimen, the matrix of the breccias often cannot be distinguished from the material of the small dikes at São João da Chapada, and, after washing in a pan, the same heavy minerals were recovered, along with an abundance of quartz crystals. The only structure preserved in the weathered exposures is a faint banding suggestive of flow lines around the boulders. The proportion of matrix to the total bulk of the breccia varies from 15 or 20 per cent. in the more crowded examples in the Barro-Duro mine, to more than 50 per cent. in the Lavra do Pagão.

At various points in the breccias are found well-developed quartz crystals, commonly containing a large quantity of thin, thread-like needles of rutile. Some of these crystals attain lengths of 15 or 20 centimeters. The crystals occur chiefly in clusters, and their habit indicates growth in open cavities.

In all the known occurrences, the breccia is covered with an overburden of red soil of several meters thickness. This soil is identical with that of other localities and is of material quite foreign to that of the underlying rocks. The whole appearance is that of residuum of old superficial deposits. Owing to the radically different material of the overburden, the surface of the breccia is usually very sharply defined. Its attitude is by no means constant, lying in a smooth, nearly level plane in some places, and in others rising in sharp peaks. There are no reliable surface indications of the bodies of breccia. The only definite characteristic is that the area over the deposit is free from outcrops of the country rock; but this condition applies equally well to areas covered by a thick accumulation of superficial deposits. The discovery in each case was accomplished by tracing diamonds in prospecting and exploitation of the surface deposits. The only known exposures are those uncovered by mining operations. With the exception of those at Boa Vista and at the Barro-Duro, these workings are of limited lateral extent, and in no case have they penetrated the zone of weathering.

In view of the unsatisfactory nature of the exposures, any attempt to formulate a theory of origin of these breccias is bound to meet with difficulty. All present data indicate that the breccias owe their existence to the intrusion of a partially cooled, plastic magma of basic composition, which entrained fragments of the country rock as it forced its way upward. This hypothesis is borne out by the characteristics of the included fragments, by the fact that minerals undoubtedly of primary origin in the matrix show no signs of abrasion, and by the striking similarity of the material of the matrix to that of the dikes at São João da Chapada, both in the mass and in the heavy minerals separated out from both sources. Against this view it may be argued that neither the wall rock nor the included fragments show signs of alteration such as one might expect in contact with igneous intrusions. A similar condition, however, prevails in the diamond pipes of Kimberley, where the igneous origin of the matrix has been definitey established. Here, in hand specimens, the wall rock and foreign fragments do not show signs of igneous contact,[3] and only under the microscope is the fusion and absorption of the thin edges of the enclosed fragments evident.[4] With a low temperature magma, such alteration would be very slight, and, in a region where weathering has progressed to such an extent as in the Diamantina district, all trace might easily have been obliterated.

In the absence of stratigraphic data, the age of the intrusions is problematic. That they took place after the regional metamorphism of the area had been effected is demonstrated by the fact that the character of the fragments included in the breccias is identical in every way to that of the country rock, wherever their source can be identified. The apparent lack of shearing in the breccias, and the open cavities implied by the free growth of the quartz crystals points to a time later than most of the moutain-making movements. The age, then, is probably not earlier than late Paleozoic, and possibly Mesozoic.

[3] Williams, Gardner F., "The Diamond Mines of South Africa," McMillan Co., New York and London, 1902.

[4] Hartog, Victor, "Petrographic Note on the Diamond-bearing Peridotite of Kimberley, South Africa," ECON. GEOL., vol. 4, p. 438, 1909.

DIAMOND DEPOSITS.

Distribution.—Diamonds are found widely scattered over an area from 30 to 50 kilometers wide, bounded on the east by the Jequitinhonha River and extending indefinitely northward from Dattas. Most of the production has been obtained from alluvial deposits formed by the present drainage systems. Deposits of this class are certainly the most numerous, and probably the richest worked to date. The distribution of these deposits affords a clue to the geographical location of probable sources. Although many rich placers have been found along the Jequitinhonha River, and all its tributaries from the west carry diamonds, the fact that these stones do not occur east of this river is most significant. Rich deposits have also been found in the tributaries of the São Francisco River which rise in the area. These decrease rapidly in size and richness as one goes west, until at distances of from 10 to 20 kilometers from the divide they cease to be of importance. This would place the source or sources somewhere near the divide which separates the two great drainage systems. The diamonds themselves might have afforded considerable information on this point, but since no records were ever kept of the characteristics of the stones from the various deposits, all valuable data which might have been collected from such sources have been lost.

Classification of Deposits.—Omitting the alluvial deposits in the terraces, flood plains and beds of the present streams, diamonds are found in the Diamantina district in the following types of deposit:

1. Residual soil.
2. Ancient placers.
   (*a*) In the Diamantina conglomerate.
   (*b*) In the basal conglomerate of the Caraça quartzite.
3. Breccia deposits.

Deposits in Residual Soil.—A small production has been maintained from the earliest times by washing the soil at various points. The diamonds are derived from nearby sources in the country rock. A rough concentration has been effected by creep,

assisted in some cases by the action of sheet floods. Occurrences of this type are of little importance except as they serve as a guide to larger deposits in the neighborhood.

Ancient Placers.—Diamantina Conglomerate. It has been found profitable to work the Diamantina conglomerate in many places. Here, some segregation of values has been brought about by the action of currents during deposition, but the tendency of the diamonds to occur in well defined zones of concentration is less marked than in fluviatile deposits. As far as one can rely on the oral reports of local dealers and prospectors, a considerable production has been obtained from this source in the past.

Ancient Placers.—Caraça Conglomerate. In several localities, diamonds have been recovered in large quantities from the conglomerate at the base of the Caraça quartzite. There are no reliable records of the total production from this source, but a rough idea of the importance of these deposits can be obtained from the size of the great open cuts at Sopa, Guinda, Dattas and many smaller workings between.

Breccia Deposits.—In six different localities, diamonds have been extracted in considerable quantity from the matrix of the breccias described under "Igneous Rocks". Of these deposits, the oldest and best known is that on the Barro-Duro property at São João da Chapada, which was discovered in 1840. Besides examining the matrix of the breccia in this mine, samples of the small dikes which cut the wall rock were also panned. No diamonds were recovered in these tests, but de Bovet,[5] and independently, Gorceix,[6] state that diamonds were recovered from these dikes under their personal supervision.

These deposits are worked intermittently by local operators, either individually or in groups; but engineering problems present difficulties which are unsurmountable with the primitive methods and inadequate capital at the disposal of the miners. Production, therefore, is very small.

[5] de Bovet, A., "L'Industrie Minérale dans la Province de Minas-Geraes," *Annales des Mines*, 8ième Série, Tome III., ff. 85–208. Paris, 1883.

[6] Gorceix, H., "Brazilian Diamonds and their Origin." *Pop. Sci. Monthly*, vol. XXI., pp. 610–620, 1882.

The diamonds do not appear to be distributed evenly through the breccia; but until intelligent development work is done, and accurate records kept, it will be impossible to make any definite statement as to their distribution.

Character of the Diamonds.—Except in the early days of the industry, when operations were conducted under strict government supervision, and with slave labor, diamond mining in Brazil has always been conducted in the most haphazard manner. Much of the mining has been done by "faiscadores," or prospectors, who work when and where they please and often hold diamonds for long periods before disposing of them, mixing in one parcel the stones from several deposits while they are hording them. Even where mining has been conducted by partnerships or groups, the clean-ups, from several deposits have often been thrown together, reaching the market in mixed lots. In this way, many valuable data as to the characteristics of the diamonds from the different localities have been lost.

Only small lots of diamonds from definitely known sources were seen personally. Although it is dangerous to assume too much from small samples, some broad statements can be made with a fair degree of certainty. Stones from recent alluvial deposits, ancient upland placers and, with few exceptions, from deposits in recent soil, present very mixed characteristics, especially in color and crystallization. A certain proportion of the stones from these deposits show unmistakable signs of wear, by broken corners, and, in a few examples, have frosted surfaces, or may actually be rounded, as produced by the rubbing of one diamond against another.

In the breccia deposits, on the other hand, the characteristics of the diamonds are far more consistent. Local cutters and dealers claim that they are so constant in each deposit, and show such differences from one deposit to another, that they can identify the mine from which any given parcel was produced. As a rule the stones are small, the general average ranging from 1/10 to 1/2 carat in the various deposits. A considerable number weigh from one to four carats each and ten carat stones are not uncom-

mon. The color is a good blue-white. The stones are of excellent gem quality, and generally only two or three per cent. are unfit for cutting. The diamonds are said to exhibit a toughness not known in the African gems. The crystallization is fairly regular, octahedral forms predominating. In many cases, the faces of the crystals approximate spherical rather than plane figures. This is noticeable even among the octahedra, and many of the higher forms are almost perfect spheres. In no case was any sign of wear noted in any of the diamonds found in the breccias.

Minerals Accompanying the Diamonds.—Wherever diamonds are recovered, whether from recent alluvial deposits, ancient upland placers or the breccias, a certain group of minerals is practically always found in the concentrate. The Brazilian prospectors have long recognized the significance of this group as a guide to diamonds, and have given it the name "formação." There is naturally some variation in the relative abundance of the minerals of this group in different localities. Frequently, a mineral which appears in conspicuous quantities in one deposit may be lacking in another. On the whole, however, they are remarkably constant and deserve the title "satellites of the diamond." The following list, in the general order of abundance, while not complete, gives a comprehensive idea of the nature of these minerals:

Quartz crystals	Abundant
Opalescent quartz	
Rutile	
Anatase	
Ilmenite	
Kyanite	
Magnetite	Occasional
Hematite	
Garnet	
Tourmaline	

Monazite Zircon Staurolite Corundum	Rare

This list brings out two very significant facts—first, the similarity of the mineral species to those found accompanying the diamond in the African deposits, and, second, the identity of these minerals with those found in the dikes associated with the breccias. It is also important to note that in all alluvial deposits, whether ancient or modern, these minerals are rolled and worn, in contrast to their fresh, clear-cut appearance in the breccias and dikes.

ORIGIN OF THE DIAMONDS.

As more work is done, and the district receives further study, additional facts will be brought to light which will increase our knowledge of the diamond deposits and which will clear up many points, now doubtful, concerning their origin. One point is clear, however, from the present investigation, namely, that as far as the recent alluvial deposits are concerned, there are two distinct classes of source, (1) in the Caraça conglomerate, and (2) in the breccias.

Sources in the Caraça Quartzite.—There can be no doubt that large quantities of diamonds were liberated from the outcrops of the basal conglomerate of the Caraça quartzite by weathering, removed by erosion and reconcentrated by recent streams, and some writers have claimed that the diamonds have originated in the quartzites themselves. This hypothesis is at variance with what is known of the origin of the diamond in other parts of the world. On the face of it, it is far more likely that the diamonds occur in the conglomerate as in an alluvial deposit, and were derived from some foreign, primary source yet to be discovered. This conclusion is borne out by the character of the diamonds, both in the mixture of physical characteristics and in the signs of wear, and by the worn character of the attendant minerals.

Sources in the Breccias.—All data collected to the present time point to the conclusion that, in the breccia deposits of the Dia-

mantina district, one is dealing with a source of diamonds similar in every essential respect to the well known diamond pipes of Kimberley and Pretoria, South Africa. It is beyond the scope of this paper to draw a complete parallel; but it is certain that these deposits constitute a primary source in this district. A recapitulation of the various points brought out in the present investigation will serve to emphasize this conclusion.

1. The geographical position of the breccia deposits is in that part of the area where, judging from the general distribution of the alluvial diamonds, one would expect the source to be.

2. The breccias are evidently of igneous origin as shown by

(*a*) the mode of occurrence;
(*b*) the character and distribution of the included fragments;
(*c*) the occurrence in the matrix of minerals in fresh condition which are undoubtedly of primary origin;
(*d*) the practical identity of the material of the matrix with that of associated dikes which are certainly igneous.

3. Neither the diamonds nor the associated minerals recovered from the matrix of the breccia show the signs of wear usual in the alluvial deposits.

4. Diamonds are found only in the matrix of the breccias.

5. Diamonds from the breccias show peculiar and consistent characteristics for each deposit, in contrast to the mixed characteristics displayed by those from the alluvial deposits.

Conclusions.—The fact that diamonds are found in the basal conglomerate of the Caraça quartzite, which is certainly much older than the breccias, may be used as an argument against the hypothesis that the breccia deposits are original sources of these gems. A similar condition, however, has also been noted in South Africa, where the significance of pipes as primary sources of diamonds has been established. In some of the Vaal River diggings, diamonds are derived from beds older than any known diamond pipes, and individual stones have characteristics different

from those of the recognized primary deposits. This mode of occurrence simply implies two distinct sets of sources, separated by a great time interval, and presents a problem quite outside the present discussion. Until the geology of the area is studied in greatest detail and the sedimentation of the Caraça quartzite thoroughly worked out, it is unlikely that any clue will be obtained as to the location of the older sources. Such deposits, if they have not been entirely eroded away, will probably be found to be metamorphosed almost beyond recognition, and will most certainly be covered with a great thickness of the Caraça quartzite, unless they should happen to occur in one of the small areas from which this formation has been removed.

Many points bearing on the origin of diamonds in general are far from being established. In the South African pipes, the diamonds were long thought to have been formed in the intrusive igneous rock; but the occurrence of broken crystals in what was supposed to be the mother rock, and the discovery of diamonds included in foreign fragments of a deep-seated rock (an eclogite), indicate that the diamonds were derived from older, deep-seated sources, and were carried upward by the intrusions found in the pipes and associated dikes. If a similar phenomenon were proved in the case of the Brazilian breccias, it would explain the anomalous presence of kyanite and monazite in what is apparently a basic rock. But whether the diamonds were formed in the intrusive rock, itself, or whether they were torn by it from some deep-seated source, all evidence obtained to the present bears out the conclusion that the breccias of the Diamantina district are sources of diamonds analogous to the pipes of South Africa.

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CERTAIN MAGMATIC TITANIFEROUS IRON ORES AND THEIR ORIGIN.[1]

PART I.

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INTRODUCTION.

THE problem of the origin of the titaniferous iron ore deposits has long attracted the attention of geologists. A few deposits have been thought to inject the country rock as dikes but most have been considered to have been formed by magmatic segregation. Some segregations have been considered marginal and others central. Some marginal segregations have been explained by liquation, sinking of early formed crystals, Ludwig-Soret effect, gaseous transfer, convection, diffusion, and gaseous tension. The origin of the central segregations has been an even

[1] An extract from a dissertation presented to the Faculty of Yale University as part requirement for the degree of Doctor of Philosophy.

[2] S. F. Emmons Memorial Fellow in Economic Geology, 1927–28.

greater enigma. The present study was undertaken to investigate this problem. But the origin of certain so-called marginal segregations also offered an attractive field for study on account of the recent emphasis on processes of differentiation involving the difference in behavior of two phases, for example liquid and crystal.[3] It was felt that a re-examination of the field occurrences was necessary, particularly in view of the fact that in many of the deposits the iron ore minerals have crystallized later than the silicates, and this fact has not been given proper consideration in many explanations previously advanced for their origin. Another problem is raised when it is noted that some deposits supposedly belonging to the marginal segregation type are not found in marginal positions.

The writer found that most of the ore bodies inject the country rock as a magma. This raises the problem of the origin of the magma, the process that produced it, and the cause of the localization. An attempt is made to answer these questions in the discussion of some of the deposits.

Field Work.—As originally planned the field work was to have been done largely on the deposits in the anorthosite near Lake Sanford, N. Y. The deposits in gabbro near Elizabethtown, N. Y., presumably belonging to the marginal segregation type, were to be visited for comparison. However, the latter showed a number of unexpected features, so they were given more study than was originally planned. During the course of the work it was considered advisable to extend the observations to other fields for the purpose of comparison and check. Consequently, the ilmenite deposits near Ivry and St. Urbain, Quebec and several titaniferous

[3] Bowen, N. L., "Later Stages in the Evolution of Igneous Rocks," *Jour. Geol.*, 23, Sup. 1915; "Crystallization-Differentiation in Silicate Liquids," *Am. Jour. Sci.*, 29, pp. 175–191, 1915; "Crystallization Differentiation in Igneous Magmas," *Jour. Geol.*, 27, pp. 393–430, 1919; "Deformation of Crystallizing Magma," *Jour. Geol.*, 28, pp. 266–267, 1920; "Differentiation by Deformation," *Proc. Nat. Acad. Sci.*, 6, pp. 160–162, 1920; "Crystallization Differentiation," *Geol. Mag.*, 57, pp. 238–239, 1920. Grout, F. F., "Internal Structures of Igneous Rocks; Their Significance and Origin; with Special Reference to the Duluth Gabbro," *Jour. Geol.*, 36, pp. 434–458, 1918; "Two-Phase Convection in Igneous Magmas," *Jour. Geol.*, 26, pp. 481–499, 1918; "A Type of Igneous Differentiation," *Jour. Geol.* 26, pp. 626–658, 1918; "Movements in Crystallizing Magma," *Jour. Geol.* 28, pp. 256–264, 1920.

magnetite deposits in Ontario were visited briefly. A short visit was also made to some of the chromite deposits in the vicinity of Coleraine, Quebec, to compare them with the titaniferous iron ore occurrences.

Acknowledgments.—The writer wishes to acknowledge his indebtedness to the Tahawus Club for permission to examine the deposits in the vicinity of Lake Sanford, and to Mr. David Gallagher, who rendered very efficient service as field assistant and did much to expedite the field work. The writer is further indebted to Professor Alan M. Bateman, who suggested and outlined the problem and gave criticism and advice freely; to Professor Adolph Knopf for criticism, advice, and discussion of the problems of petrography and petrogenesis involved in this problem; and to Dean C. H. Warren for discussions, particularly of the origin of cumberlandite, urbainite, and the microstructure of the ore minerals. He also wishes to record his grateful appreciation of the award of the S. F. Emmons Memorial Fellowship, which enabled the field and laboratory work to be carried on.

GENERAL CONSIDERATIONS.

Development of the Conception of Magmatic Deposits.

The recognition of ore deposits formed by accumulation of pyrogenetic minerals is comparatively recent, yet some of the earlier writers suggest their formation by this means. In 1811 Breislach,[4] an Italian geologist, suggested that many ore deposits might have been formed by separation of minerals from a magma and concentrated by specific gravity or chemical affinity. In 1876 Sjögren[5] suggested that the titaniferous ore deposits of Taberg had the same origin as a plutonic rock. Von Groddeck[6] regarded the Taberg deposit as a magmatic segregation. Tornebohm[7] says

[4] Emmons, S. F., "Theories of Ore Deposition Historically Considered," *Geol. Soc. Amer. Bull.* 15, p. 12, 1904.

[5] Sjögren, A., *Geol. Fören, Förh.*, III., p. 42, 1876.

[6] Von Groddeck, B., "Die Lehre von den Erzlagerstätten," pp. 142, 278, Leipzig, 1879. Cited by Hummel, K., ECON. GEOL., 20, p. 299, 1925.

[7] Törnebohm, A. E., *Geol. Fören. Förh.*, 5, p. 610, 1881.

that the Taberg ore "may be regarded as a variety of hyperite rich in iron ore." He did not discuss the process of differentiation that gave rise to the deposit.

In 1893 Vogt [8] published his classic paper on the magmatic segregation ore bodies, in which he attempts to explain the concentration of the ore on a physical-chemical basis. He outlines the following methods: (1) The ore minerals may crystallize and then aggregate in the still fluid mother-liquor; (2) The minerals that crystallize and aggregate in the magma may be resorbed and form a modified magma; (3) There may be a diffusion in the liquid state so that a concentration may result (Soret and Gouy-Chapeyron effects). At that time Vogt rather favored (3). In 1894 [9] Harker ascribed the concentration of the iron ores along the margin of a gabbro mass to the diffusion toward a cooler surface with attendant crystallization. In 1897 Teall [10] made a very astute suggestion. Describing the basalts, in which the iron ores crystallized last, he says: "In view of the evidence thus furnished of the concentration of the iron, one is tempted to speculate as to the results that might follow if the process were carried still further. Magnetite forms the matrix of the cumberlandites of Rhode Island and Taberg in which olivine and feldspar occurs as phenocrysts. Can it be that in some, at least, of these cases we see the extreme results of the process indicated above?" Kemp,[11] as the result of his important work in the Adirondacks, concluded that the differentiation of the iron ore and the country rock must have taken place while they were both liquid. He favored the separation of the iron ores as an immiscible liquid early in the cooling.

Since 1900 the interpretation of the deposits has been similar to

[8] Vogt, J. H. L., "Bildung von Erzlagerstätten durch Differentiationprozesse in basische Eruptivmagmata," *Zeit. f. prakt. Geol.*, I., pp. 4–11, 125–143, 257–284, 1893.

[9] Harker, Alfred, "Carrock Fell, A Study in Variation of Igneous Rock Masses," *Quart. Jour. Geol. Soc.*, pp. 311–325, 1894.

[10] Newton, E. T. and Teall, J. J. H., "Rocks and Fossils from Franz Josef Land, etc.," *Quart. Jour. Geol. Soc.*, 53, p. 488, 1897.

[11] Kemp, J F., "Titaniferous Iron Ore of the Adirondacks," U. S. Geol. Survey, 19th Ann. Rept. 1897–1898, Pt. III., p. 384.

that of the earlier investigations mentioned. According to Daly,[12] "most basic segregations and probably all orbicular granites, diorites, and gabbros are direct evidence of the emulsion stage." He also says,[13] "that gravity has controlled the segregation of the larger bodies of magmatic iron ore is already clear." He departs from some of the previous ideas when he says,[14] "Mere gravity differentiation in liquid magma cannot explain certain small basic or ultra-basic phases in intrusive bodies. Contact segregations of magnetite, ilmenite, mica, tourmaline, etc., are often found. There is a growing belief that they are due to upward transfer of emanating gases." In 1913 Lindgren says:[15] "In the formation of the titanic ore deposits of the Adirondacks, the ilmenite probably crystallized first and settled to the bottom. . . . If the components of a magma are not miscible, a liquation will take place and the heavier parts, perhaps the sulphides and the iron ores, will settle to the bottom." In the 1919 edition of his book he makes substantially the same statement and adds,[16] "The fact that magnetite and ilmenite form dikes suggests differentiation before consolidation." In the last edition[17] he expresses the belief in the sinking of the ilmenite, its re-fusion at depth and re-injection to form the ore bodies in anorthosite.

The iron ores associated with the platinum deposits of the Urals described by Duparc[18] are products of magmatic differentiation. Spurr[19] attempts to explain one of these, Taguil, by "gaseous tension". The exact physical or chemical basis of the phenomenon is not clear to the writer, although "gaseous tension" has been identified with[20] the Soret effect. In explaining the

12 Daly, R. A., "Igneous Rocks and Their Origin," p. 226, 1914.

13 Daly, *ibid.*, p. 454.

14 Daly, *ibid.*, p. 247.

15 Lindgren, Waldemar, "Mineral Deposits," 1st Ed., 1913, p. 740.

16 *Op. Cit.*, 2d Ed., 1919, p. 786.

17 *Op. Cit.*, 3d Ed., 1928, p. 864.

18 Duparc and Tikonowitch, "Le Platine et les Gites Platinifères de l'Oural et du Monde," Geneva, 1920.

19 Spurr, J. E., "Ore Magmas," II., p. 575, 1923.

20 Smith, S. W., "Liquation in Molten Alloys and its Possible Geological Significance," Inst. of Min. and Met. Bull., 257, p. 1, London, 1926.

cores of dunite surrounded by pyroxenite and gabbro [21] Spurr says, " Not gravity but some other force has arranged these silicates in the order of their deposition, working from the periphery inward, or from the mass of the intrusion outward. Such a force in gaseous tension and I submit the hypothesis that this is the force in question, working from the mass outward toward the periphery." To account for the association of ilmenite and pyroxene he [22] says, " Ilmenite is similarly closely allied as to conditions of fixation and therefore of hypothetical vapor tension with pyroxene, and, therefore, does not as a rule separate far from it." Unfortunately Spurr does not define his terms or make clear the exact mechanism of the process. One is in doubt about the meaning of " gaseous tension " and " vapor tension."

Rastall's [23] idea of the mechanism of differentiation may be gained from the following quotation, " from basic magmas the metallic ores tend to separate first, and to sink to the bottom: from the acid magmas they tend to separate last and rise to the top." He applies the generalization largely to sulphide deposits, in the concentration of which, he attributes the difference in behavior largely to the presence of volatile constituents in the more acidic rocks.

In discussing the formation of ore deposits of the oxide and sulphide type, Shand [24] says: " A sharper distinction between oxidic and sulphidic segregations is found in the period of crystallization of the ore-minerals. The oxides are always found to have crystallized before the associated silicates, and the sulphides, when they are abundant, after the silicates." He discusses the various methods that might bring about the concentration of the ore in the rock, but concludes that the problem needs further investigation before it can be settled.

Such, in brief, are some of the hypothesis that have been advanced to account for segregation ore deposits. Subsidence of early-formed crystals, immiscibility, gaseous tension, gaseous transfer, Soret effect, and re-fusion of sunken crystals have all been invoked to explain them.

[21] Spurr, *op. cit.*, p. 576.

[22] Spurr, *op. cit.*, p. 580.

[23] Rastall, R. H., " Physico-Chemical Geology," p. 199, 1927.

[24] Shand, S. J., " Eruptive Rocks," London, 1927.

MAGMATIC SEGREGATION—DEFINITION.

The term " magmatic segregation " has been used by economic geologists to designate the ore deposits of pyrogenetic minerals, which are contrasted with the deposits formed by deposition from aqueous or gaseous media. According to the usage of petrologists, the term segregation has a definite meaning, and since the ore bodies are really igneous rocks, their terminology may be investigated. Holmes [25] says: " Segregation.—A term applied to authigenous mineral aggregates, in masses or streaks, occurring in igneous rocks, and representing early products of crystallization from the same respective magmas." According to Iddings,[26] " Segregations have also been called endogenous inclusions. They appear to have been early crystallizations in the magma, ..." Vogt in his classical work on these deposits followed the usage of the petrologists in this term, and it has been more or less adhered to by later students of economic geology.

The fact that the iron ores in many places crystallized after the silicate minerals has been known for a long time, but it has been especially emphasized by Tolman and Rogers,[27] who attribute it to the presence of mineralizers. They point out that if the iron ores separate last instead of first, the general opinion that the iron ore bodies are magmatic segregations will have to be revised, if segregation is to retain its implication of early crystallization. Subsequently Singewald [28] considered the influence of the volatile constituents in the formation of the titaniferous iron ore deposits.

In the localities studied by the writer the minerals composing the ore bodies were liquid after the host rock was solid, and, therefore, they cannot be termed segregations because they are not concentrations of the early crystallizing minerals in place. In the opinion of the writer, the term magmatic segregation should

[25] Holmes, Arthur, " The Nomenclature of Petrology," p. 208, 1920.

[26] Iddings, J. P., " Igneous Rocks," vol. 1, p. 254, 1909.

[27] Tolman, C. F., and Rogers, A. F., " A Study of the Magmatic Sulphide Ores," Leland Stanford Junior University Publication, 1916.

[28] Singewald, J. T., Jr., " The Rôle of Mineralizers in Ore Segregations in Basic Igneous Rocks," Johns Hopkins Univ., Contributions to Geology, pp. 24–35, 1917.

be restricted to deposits, in which there is a concentration of the early formed minerals along the margins such as Carrock Fell [29] or some chromite deposits in peridotite.

It is necessary to find a term to distinguish these intrusive bodies from the magmatic segregations. From the petrologist's point of view they are melanocratic diaschistic dike rocks. This term is too cumbersome for general use and it does not distinguish them from lamprophyres. They correspond very closely to the conception expressed by "ore magma" and "veindike"; however, Spurr does not restrict these terms to injected bodies of pyrogenetic minerals but also applies them to deposits containing minerals not of pyrogenetic origin. Most geologists consider these deposits of pneumatolytic or hydrothermal origin. It is proposed to call the intrusive deposits of pyrogenetic minerals "magmatic injections".[30]

It is believed that the magmatic injections were true magmas, but Lindgren [31] specifically excludes oxide melts from magmas when he says, "A magma may yield gases, or aqueous solutions rich in silica; it may also yield melts of the oxides of iron, titanium, or chromium; or finally it may yield sulphide melts or sulphide solutions. These products should not be termed magmas but *magmatic products.*" According to a footnote on the same page a melt is to be considered a magma when it contains over 25 per cent silicate minerals. In other words two products which may be derived by the same process of differentiation may be separated at an arbitrary point of 25 per cent silicate mineral content and the one called a magma and the other a magmatic product. In the opinion of the writer a magma and a magmatic product should be distinguished by other means than the composition. When a magma, which is liquid principally due to head, solidifies, the product has a volume nearly that of the original liquid. Gases deposit solid material, which has a volume only a small fraction of that of the vapor, and the amount of material depos-

29 Harker, A., *op. cit.*

30 This term has been used by Prof. Alan M. Bateman, and was suggested to the writer by him.

31 Lindgren, Waldemar, "Mineral Deposits," 3d Ed. p. 125, 1928.

ited from an aqueous solution is only a small fraction of the total amount of the solution. In general the magma has not the power of penetrating the rock that it intrudes to an extent as great as a gas or aqueous solution.

It is believed that the ore deposits studied were magmas—products of magmatic differentiation—and that they were injected into the country rock, and are to be considered magmatic injections rather than magmatic segregations.

CLASSIFICATION OF THE DEPOSITS.

The foregoing differences of opinion regarding the origin of the deposits make classification difficult. Vogt's classic division of the magmatic segregations into, oxide, sulphide, and metal deposits has been used extensively, and has the advantage of separating types which have other differences than the mineralogy. Shand [32] uses this classification, and states it is of genetic significance because in the oxide types the ore crystallized before the silicate minerals, but such was not the case with the sulphides.

Recently Vogt [33] has proposed a genetic classification of deposits formed by magmatic "segregation," as follows:

I. Formation due to crystallization differentiation.

(a) In the proto direction.

(b) In the restmagma direction.

II. Formation due to segregation of material originally dissolved in the silicate magma and precipitated in the liquid phase by refrigeration.

Vogt classes the titaniferous iron ores as proto enriched deposits under I. (a). Scheumann [34] in discussing the origin of certain lamprophyric magmas gives two types of differentiation, which he calls accumulative and fusive, corresponding to the groups I. (a) and I. (b) of Vogt. Zavaritsky [35] accepts these

[32] Shand, S. J., Eruptive Rocks, p. 317, 1927.

[33] Vogt, J. H. L., "Magmas and Igneous Ore Deposits," Econ. Geol., 21, p. 309, 1926.

[34] Scheumann, K. H., "Zur Genese alkalisch-lamprophyrischer Gangesteine," *Centralbl. Mineralogie*, Jahrgang 1922, pp. 518–520.

[35] Zavaritsky, A. N., "Classification of Magmatic Ore Deposits," Econ. Geol., 22, p. 679, 1927.

terms and adds a new type, which he calls "syntectic liquation deposits, in the formation of which the splitting up of the magma is caused by the infusion of country rock (limestone)." His classification is:

A. Deposits formed by crystallization differentiation.

(1) Accumulative deposits.
(2) Fusive deposits.

B. Liquation deposits.

(1) Straight liquation deposits.
(2) Syntectic liquation deposits.

He [36] classifies the titaniferous ore deposits as fusive.

The writer thinks that the terms are poorly chosen. The words "accumulative deposits" do not imply what accumulated—whether it was a liquid or solid. Similarly "fusive" gives no indication of the precise nature of the process. Vogt's proto enriched and restmagma enriched seem preferable. Liquation is a much abused term. Liquation [37] or eliquation has been used in metallurgy to designate the process of separating an alloy by heating it to melt the more fusible but not the less fusible parts, and thereby bring about separation. Used in a geological sense it is defined by Holmes [38] as: "A process of differentiation in which two immiscible liquids separate from their common solution (*e.g.*, from a magma)." The metallurgists have also another use of the term: Smith [39] says, "The sense in which the term 'liquation' is used in this paper is the sense in which it has been used by metallurgists to denote certain occurrences of segregation in alloys, more particularly in the alloys of the so-called 'precious' metals." Benedicks [40] identifies the effect with the Ludwig-Soret phenomenon, and Smith [41] suggests it may be the same as Spurr's

[36] Zavaritsky, *op. cit.*, p. 680.

[37] Raymond, R. W., "A Glossary of Mining and Metallurgical Terms," *Amer. Inst. Min. Eng.*, 9, p. 130, 1888.

[38] Holmes, Arthur, "The Nomenclature of Petrology," p. 143, 1920.

[39] Smith, S. W., "Liquation in Molten Alloys and its Possible Geological Significance," Inst. of Min. and Met. Bull., 257, p. 1, London, 1926.

[40] Benedicks, Carl, "Metallographic Researches," p. 285, McGraw Hill, 1926.

[41] Smith, S. W., *op. cit.*, p. 36.

possible to advance a tentative explanation for the deposits in anorthosite but cannot suggest one that fits the deposits in gabbro. It seems then that the division, which is now on a lithological basis, has a genetic significance, which may appear as the result of further study of the problem. Igneous iron ore bodies in other than anorthositic rocks are unimportant. Magnetite is occasionally found in syenite as an injected body conforming to the primary structure or cutting across it. The deposits studied by the writer that rank as possible sources of iron ore are either in anorthosite or gabbro.

Although this classification is proposed primarily for the deposits of titaniferous iron ore studied by the writers, it is capable of a broader application. Deposits of type 1*A* and 2*A* are restricted to the iron ores: the only concentrations of metallic minerals commonly found with anorthosite are those of iron ore. If there had been the separation of an immiscible magma, as is probably the case in some sulphide deposits, the resulting deposit might be classed under either 1 or 2 depending whether it settled to the bottom and remained there or was concentrated and injected into the parent rock or into other rocks. Where economically valuable minerals are concentrated in a certain rock the whole rock must be regarded as constituting the deposit and classed accordingly. Examples are: corundum in some syenites, and platinum in some dunites and norites.

GEOLOGICAL OCCURRENCE OF THE DEPOSITS.

All the deposits studied by the writer that rank as possible sources of titaniferous iron ores are in anorthosite or gabbro and related rocks. The larger number of those described are from the Adirondack Mountains in New York. Here a mass of anorthosite forms the core of the mountains with small areas of gabbro within and around it. The age relations of the two rocks are uncertain but they both contain deposits of iron ore. The deposits in Quebec and Ontario are found under similar conditions except in one instance where a deposit is in gabbro unrelated to anorthosite. Another type of deposit is that associated with the pegmatites of

the silica-deficient rocks, notably the corundum and nepheline syenites or with gabbro pegmatites. The ores of this type are of scientific interest only.

DISCORDANT BODIES IN ANORTHOSITE.

The principal representatives of the discordant bodies in anorthosite are found in the vicinity of Lake Sanford in the Adirondack Mts. and at Ivry and St. Urbain, Quebec. The New York deposits consist of magnetite, ilmenite, and spinel. The Quebec occurrences consist of ilmenite and spinel, but the two are genetically similar; hence they are classed together.

Lake Sanford.

In the vicinity of Lake Sanford there are three important ore bodies that belong to this group—Sanford Ore Bed, Millpond, and Ore Mountain. The position, extent, and general relationships of the deposits have been discussed by Emmons,[43] Kemp,[44] Newland,[45] and Singewald[46] so their geological relations need only be considered. The main contacts of the ore bodies are not exposed; however, some minor contacts can be found where the ore intrudes masses of the country rock. Several small bodies, similar in composition to the large masses, intrude the anorthosite, giving on a small scale the relations of the larger masses.

The Sanford Hill Ore Body.—The Sanford Hill ore body is on the east side of Lake Sanford. There are two open cuts; the old pit, near the north end of the deposit, from which some ore was extracted, and the pit near the old mill, from which the ore was taken for the experimental run at Mineville[47] in 1913.

[43] Emmons, Ebenezer, Final Report on the Second District; New York Natural History Survey, p. 244, Albany, 1842.

[44] Kemp, J. F., "Titaniferous Iron Ores of Adirondacks," U. S. Geol. Survey, 19th Annual Rept., III., pp. 409–416, 1897–1898.

[45] Newland, D. H., "Geology of Adirondack Magnetic Iron Ores," New York State Mus. Bull., 119, pp. 155–164, 1908.

[46] Singewald, J. T., Jr., "Titaniferous Iron Ore in the United States," U. S. Bureau of Mines, pp. 66–76, 1913.

[47] Bachman, F. E., "The Use of Titaniferous Ore in the Blast Furnace," Year Book, Iron and Steel Industry, 1914, pp. 370–419.

FIG. 1. Reaction rim developed at contact of iron ores (opaque) and plagioclase, which shows many inclusions arranged parallel to the side pinacoid. Hornblende and biotite are against the iron ores and garnet is developed against the plagioclase. From Sanford ore body, Lake Sanford. Crossed nicols. × 14½.

FIG. 2. Tongue of ilmenite (dark) cutting the plagioclase and shoving aside the twinning lamellæ. Note the displacement of the twin bands and the strain extinction. Plagioclase (P) contains antiperthitic rods. Ivry Mine, Ivry, Quebec. Crossed nicols. × 16.

FIG. 3. Ore from the Coulomb Pit, St. Urbain, Quebec, showing the interstitial character of the ilmenite. It appears to corrode the hypersthene. × 40.

FIG. 4. Reaction rim around plagioclase from Ore Mountain, Lake Sanford showing pyroxene and hornblende developed close to the ore minerals and garnet at a greater distance. Notice the narrow rim free from inclusions in the plagioclase and the manner in which the feldspar is cut across by the ore. Nicols crossed. × 14½.

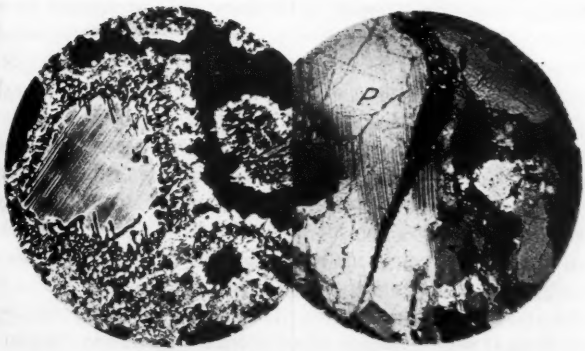


Fig. 1 .

Fig. 2.

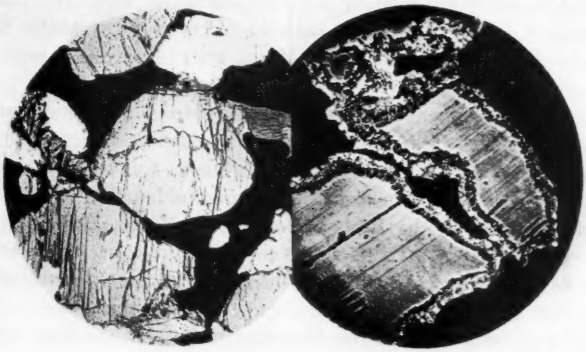


Fig. 3.

Fig.4.

The magma, which solidified as an aggregate of magnetite ilmenite, and subordinate spinel, intruded the anorthosite and engulfed blocks of it. The blocks were displaced and rotated, as shown by mappable variation in lithology and direction of foliation, and they were also corroded. Aggregates of plagioclase anhedra, which, with the ore as a groundmass, have a decided resemblance to a glomeroporphyritic[45] texture, occur. Single plagioclase anhedra inclosed by ore resemble porphyritic feldspars. These xenocrysts are angular and subangular, but some have the characteristic outlines of plagioclase phenocrysts, although they are likely to be shattered. The xenocrysts are invariably surrounded by a reaction rim in which garnet is a prominent constituent. Iron ore cuts some of the anorthosite blocks in a manner suggesting replacement.

Millpond Ore Body.—In the vicinity of the Mill Pond Ore Body there is some evidence of an internal structure in the anorthosite, but it can be seen only where exposures are unusually good. For example along the Hudson River from the point where it leaves Henderson Lake to where it turns south, the rocks show well-defined bands from 10–15 feet thick with a N.-S. strike and a dip of 20° east. The pseudo-stratification is a textural rather than a mineralogical variation, although one band may show upon close examination more mafic minerals than another. East of the Hudson there is evidence for a similar structure with the same dip in the anorthosite, although a short distance farther east the dip is reversed. The exceptionally coarse grained Millpond Ore cuts across this structure. Feldspar xenocrysts are not so common as in the exposures near the old mill, but they show similar reaction rims.

Ore Mountain.—The Ore Mountain body is on the west slope of Mount Adams. The relationships are apparently the same as those in the Mill Pond body but the contacts are not exposed.

In the area around Lake Sanford the physiographic evidence indicates considerable faulting. It may be only a coincidence that the ore bodies are exposed where there is evidence of considerable

[48] Glomeroporphyritic, a term proposed by Judd in 1886 for the texture produced by the segregation of numerous crystals of the same mineral into compact and conspicuous groups giving a porphyritic aspect.

displacement. The faulting makes the determination of the relationship between the different classes of ore bodies in the locality impossible.

Petrography.—The microscope shows that in the vicinity of Lake Sanford the predominant rock is anorthosite, with a basicity ranging from An 50 to An 55. Where the rock is not granulated it consists of an interlocking mosaic of plagioclase anhedra with a few interstitial grains of iron ores and pyroxene. The plagioclase usually shows numerous inclusions of opaque and non-opaque minerals, which seem to give color to the anorthosite because where the plagioclase is sheared it is colorless and the inclusions are absent or few in number. One of the most noticeable features of the anorthosite is the reaction rims that surround the iron ore minerals and other dark minerals of the rock. A typical example is shown in Fig. 1. The same minerals are developed around magnetite, ilmenite, and spinel and their arrangement is similar. Biotite and hornblende occur close to the ore, and a colorless pyroxene at a greater distance, with garnet still farther out. The iron ore minerals (including spinel) are molded on the silicate minerals with which they are in contact. In a few slides, other minerals are found, notably a carbonate and scapolite, but they are present in minor amounts and are not characteristic of the deposits as a whole. The microscopic evidence indicates that the iron ores crystallized after the silicate minerals and that they corroded and embayed the earlier minerals.

Mineralography.—All the ores of this type from the Lake Sanford locality show many features in common. They consist of magnetite, ilmenite and spinel. Under the microscope they show: ilmenite, and magnetite containing ilmenite and spinel lamellae. The nature and significance of the intergrowths will be considered more fully in a later section on mineralography.

Ivry, Quebec.

The Ivry Mine, Terrebonne County, Quebec, is in the Morin anorthosite area[49] and is important not only because it is one of

[49] Adams, F. D., "Geology of a Portion of the Laurentian Area Lying North of the Island of Montreal," Geol. Surv. Can. Ann. Rept., viii, pt. J, 1895.

the largest ilmenite bodies studied, but also because it throws some light on the manner of formation of the class of deposits as a whole. This deposit shows clearly the intrusive nature of the ore. There are several outcrops of ore on the anorthosite hill on which the deposit is located. The development work does not show whether they are part of a continuous body or are separated. A quarry on the north face of the hill offers a good place to ascertain the relationship of the ore and country rock. In most places the contact is sharply defined but in some places disseminated ore is found as the contact of the orebody is approached. However, close inspection shows that these grains are interstitial to the plagioclase and the ore appears to have been injected. The main ore body contains many inclusions of the plagioclase arranged parallel to the direction of the deposit. Some narrow dikes of ilmenite cut the anorthosite, which shows the effects of shearing along the contacts.

Petrography.—Hand specimens of the anorthosite show considerable variation in grain size, but the color is more uniform, a mauve to light chocolate being the most common. The plagioclase ranges from An 50 to An 60. Interstitial orthoclase, biotite, ilmenite, hypersthene, and diallage are found. Small non-opaque inclusions commonly cloud the plagioclase, and antiperthitic rods are especially characteristic of much of the rock.

In this deposit the microscope yields considerable evidence bearing on the method of formation of the ore. Fig. 2 shows how the plagioclase has been shoved aside by the ilmenite parallel to the twinning lamellae. The margins of the deposit as well as the included plagioclase show some suggestion of replacement but it is less well developed than around the iron ore bodies in the vicinity of Lake Sanford. It is noteworthy that the Ivry ores do not show the well-developed reaction rims; hornblende is not present at all and biotite is not common. All the evidence shows that the ore must have been injected here as a differentiate that originated elsewhere.

Mineralography.—The ore from this deposit is practically pure ilmenite with intergrown hematite except for the presence of the

plagioclase previously mentioned and a little interstitial pyrite, pyrrhotite, and chalcopyrite. The sulphides also form small veins that cut the ore body.

St. Urbain, Quebec.

The anorthosite area of St. Urbain, Charlevoix District, Quebec, described in detail by Mawdsley,[50] contains several important bodies of ilmenite. It is roughly elliptical in outline, about 18 miles long by 9 miles wide and is surrounded by diorite and syenite. The anorthosite is composed of plagioclase ranging from An 30 to An 65. The more sodic facies outcrop toward the margins of the mass and cut the more calcic varieties.

The main ilmenite deposits are grouped within an area about one mile across, which, at the nearest point, is one half a mile from the south west margin. All the deposits exhibit a marked similarity in character. The plagioclase of the country rock from all the deposits ranges between An 38 and An 45. Antiperthitic rods of potassic feldspar in the plagioclase are common. Close to the ore bodies biotite is developed in the anorthosite and the dark constituents are altered to an aggregate of serpentine and chlorite. In most places the anorthosite is quite fresh, but in the vicinity of the General Electric deposit, alteration is more evident; zoisite, sericite, and carbonate are found. The occasional dark constituents in addition to the biotite, are hypersthene and ilmenite. Mawdsley [51] says: "The order for crystallization appears to be: plagioclase starting first and continuing over a long interval; then both hypersthene and iron ore, the iron ore ceasing before the hypersthene and the latter before plagioclase; hornblende and biotite commenced after hypersthene and finished with the plagioclase." The writer could not determine the order of crystallization so completely; however, the hypersthene and iron ore are interstitial to the plagioclase and the iron ore molds itself on the pyroxene. The order of completion of crystallization would, therefore, appear to be: plagioclase, hypersthene, iron ore. The relationship

[50] Mawdsley, J. B., "St. Urbain Area, Charlevoix District, Quebec," Geol. Surv. Can. Mem., 152.

[51] Mawdsley, J. B., *op. cit.*, p. 21.

of the small amount of interstitial orthoclase to the dark constituents could not be determined.

The anorthosite is quite commonly somewhat granulated in the vicinity of the deposits. Mawdsley[52] describes it as " — a protoclastic structure indicated: (1) by the granulated state of the hypersthene; (2) by the polygonal outline of many of the plagioclase grains; and (3) by the presence of plagioclase grains with schiller inclusions mixed with grains which do not contain the inclusions and possibly, therefore, crystallized later." That the hypersthene is granulated is not a proof of protoclasic texture; if the hypersthene were not granulated and the feldspar were, it might be. The polygonal outline of the plagioclase grains might equally well be developed during cataclastic deformation. The absence of schiller inclusions in certain grains may be the result of deformation, because the inclusions tend to vanish on granulation. In the opinion of the writer the texture is protoclastic but conclusive evidence is yet to be presented.

The ore is essentially intrusive in character. It has injected the anorthosite, broken through it, and engulfed blocks of it. It is difficult to convey an idea of the irregularity of outline of the deposit. The walls are not sharply marked fissures as they are in many dikes. The sketch maps accompanying Mawdsley's memoir give some idea of their irregularity but in the field it is even more striking. The ore is, essentially, a concentration of the last crystallizing constituents derived from one part of the anorthosite and injected into another part. In some places the ore body contains plagioclase and hypersthene set in a matrix of iron ore. The silicates show a well-defined fluxional arrangement. By a decrease in the amount of silicate the ore passes into pure ilmenite with a little interstitial sulphide. The absence of chilled margins of the ore against the rock may be explained if one assumes that the ore was injected into hot anorthosite.

The Coulomb deposit may be taken as typical of deposits with the silicate minerals associated with the ilmenite and hematite. The ore consists of a very fine intergrowth of hematite in

[52] *Ibid.*

ilmenite, which forms a matrix for plagioclase, hypersthene and a few grains of apatite. This texture is shown in Fig. 3. The plagioclase is An 45 and the optical properties of the hypersthene indicate about 25 mol per cent. $FeSiO_3$.

The Furneau deposit is the closest to St. Urbain. It consists of a practically pure ilmenite-hematite intergrowth which injected an anorthosite of composition An 44. Close to the contact a little biotite is developed.

More work has been done on the General Electric Deposit [53] than on any other deposit in the vicinity and it has received more attention on account of the presence of rutile and sapphirine with the ilmenite and spinel. In most respects this deposit is similar to the others described. The ore injected anorthosite of basicity An 40, but there is considerably more hydrothermal alteration in this deposit than in the others. Biotite is developed around the margin paralleling the contacts of the deposit, and as sheaves through the anorthosite. The biotite is commonly altered to chlorite along the margins and along the cleavage.

Problems of Genesis of the Discordant Bodies in Anorthosite.

The major problem concerning the transgressive bodies is, of course, the process of differentiation by which they have been derived; to understand this it is essential to consider the nature of the ore and the country rock at the time of the concentration of the ore. One of the best modes of attack, an indirect one, appears to be through a study of the reaction rims that mark the boundaries between some ore and the country rock. An example of the contact between ore and country rock is shown in Fig. 4.

Reaction Rims.—The larger part of the literature on reaction rims has been summarized by Sederholm [54] who concludes they are formed as the result of dynamic metamorphism probably assisted by mineralizers. Vogt [55] believes that they are due to

[53] Warren, C. H., "The Ilmenite Bearing Rocks Near St. Urbain, Quebec; a New Occurrence of Rutile and Sapphirine," *Amer. Jour. Sci.*, 33, pp. 263–277, 1912.

[54] Sederholm, J. J., "On Synantetic Minerals: Finland," *Bulletin de la Commission Geologique*, No. 48, pp. 2–41, Helsingsfors, 1916.

[55] Vogt, J. H. L., "Magmatic Differentiation of Igneous Rocks," *Jour. Geol.*, 29, p. 648, 1921.

reaction in the solid state in the cooling rock and that the width of the reaction zone may be correlated with the rate of cooling. Tolman and Rogers [56] believe that the reaction rims are due to hydrothermal or pneumatolytic processes preceding the deposition of the ore. Essentially the same view is held by Foye.[57]

Kemp and Alling [58] have suggested that certain reaction rims in gabbro are due to the action of a liquid on the solid minerals. They do not discuss the nature of the residual magma but state that their evidence is derived from the chilled contact of a gabbro mass.

In a recent paper Gillson, Callahan, and Millar [59] interpret the reaction rims and magnetite as deuteric minerals due to a distillation of volatile constituents from the same magma chamber from which the gabbro containing the reaction rims was derived. This seems to be a misuse of the term deuteric. According to Sederholm,[60] who originated and defined it, the word applies to those changes, "which have taken place in direct consequence of the consolidation of the magma of the rock itself." The term pneumatolytic or hydrothermal would express their idea more correctly.

There are numerous other descriptions of reaction rims but the explanations are essentially the same as those outlined above. The writer believes that the reaction rims are due to a reaction between the crystallized mineral and the restmagma, and that they may be divided into two classes. The first class consists of those formed by the reaction between a more basic early separating constituent and a more acidic restmagma. This follows the reaction

[56] Tolman, C. F., Jr., and Rogers, A. F., "A Study of the Magmatic Sulphide Ores," Stanford University Publication, 1916, p. 22.

[57] Foye, W. G., "The Relations of the Titaniferous Magnetite Ores of Glamorgan Township, Ontario," Econ. Geol., 11, p. 665, 1916.

[58] Kemp, J. F., and Alling, H. L., "Geology of the Ausable Quadrangle," *N. Y. State Mus. Bull.*, 261, p. 58, 1925.

[59] Gillson, J. L., Callahan, W. M., and Millar, W. B., "Adirondack Studies: The Age of Certain of the Adirondack Gabbros, and the Origin of the Reaction Rims and Peculiar Border Phases Found in Them," *Jour. Geol.*, 36, pp. 149–163, 1928.

[60] Sederholm, *op. cit.*, p. 142.

series as outlined by Bowen;[61] and a typical example is the reaction rim surrounding olivine. The second type is the one in which an acidic mineral is surrounded by a more basic restmagma. This is the type with which we are concerned in the iron ore deposits. It is believed that these are due to the action of a liquid on a mineral. The evidence is as follows: The iron ore minerals, magnetite, ilmenite, and spinel, are molded on the silicate minerals including hornblende and biotite. The reaction rims surrounding the three iron ore minerals named above are identical, in mineral composition and in width when all three are found together, but in the deposits, in which ilmenite occurs with hematite alone, the reaction rims are lacking. If the rims were produced by reaction in the solid state they should vary with the mineral with which they are in contact, *i.e.*, ilmenite should have no surrounding rim. This leads to the conclusion that the reaction rims were formed before the ore minerals crystallized. That is, the ore was introduced either as a magma or a pneumatolytic or hydrothermal product. In the country rock there is little evidence of a pneumatolytic origin in the presence of alteration minerals such as zoisite, scapolite sericite and the like. Furthermore, in many of the deposits there is positive evidence that the ore was injected as a magma, as is shown by the rotation of blocks and the shoving aside of lamellae of plagioclase. Further evidence may be derived from the ilmenite-hematite deposits. If they are of pneumatolytic or hydrothermal origin they are the only evidence of such action and furthermore, near any deposit the ratio of the ilmenite to the hematite is essentially constant. If they were derived from solutions it is doubtful if this constancy of the two components would occur.

Order of Crystallization.—The order of crystallization of the constituents has an important control over the direction of differentiation; consequently this feature is considered rather fully. In discussions of ore deposits of the segregation type there has been a tendency to consider that certain constituents invariably form at

[61] Bowen, N. L., "Reaction Principle in Petrogenesis," *Jour. Geol.*, 30, p. 191, 1922.

certain points in the magma's cooling. A statement by Holmes [62] is illuminating: "The 'fundamental law of decreasing basicity' enunciated by Rosenbusch has dominated and prejudiced interpretation to such an extent that, until recent years, any departure from it was considered abnormal." Rosenbusch himself realized the many exceptions to his rule, though by many the rule was accepted without question. Since the iron ores are among the most basic minerals, they should separate among the first; but in rocks that contain many of the iron ore deposits, the more acidic minerals appear to have separated first. Enough localities have been studied to show that such departure from the rule is by no means unusual. Bowen [63] and others have pointed out that all that may be determined from a thin section of a plutonic rock is the order of cessation of crystallization and that this is commonly called the order of crystallization. If the order of beginning of crystallization is required it is necessary to study the quenched rocks, such as the effusives. However, this involves another difficulty; the minerals of effusive rocks are not the same as those of plutonic rocks, probably due to the opportunity for reaction, and to the presence of mineralizers.[64] Allowing for these differences it seems possible to determine the order of crystallization by using the evidence gained from a study of thin sections of effusive and plutonic rocks, and from experiments.

Lagorio found from experimental work on silicate melts that the glass base left in volcanic rocks does not become more acidic in composition with continued crystallization. Later, Bowen [65] investigated the system albite-anorthite-diopside, and used the results to interpret the order of crystallization of diorites and gabbros. In his system the residue is of increasing acidity, and Bowen accepts this as the general case. There is considerable

[62] Holmes, Arthur, "Petrographical Methods and Calculations," p. 349, London, 1921.

[63] Bowen, N. L., "The Order of Crystallization in Igneous Rocks," *Jour. Geol.*, 20, p. 446, 1912.

[64] Fenner, C. N., "The Katmai Magmatic Province," *Jour. Geol.*, 34, p. 698, 1926.

[65] Bowen, N. L., "Crystallization of Haplobasaltic, Haplodioritic and Related Magmas," *Amer. Jour. Sci.*, 40, pp. 161–185, 1915.

experimental evidence to show that in rocks of basaltic composition, the mafic constituents are liquid [66] for a longer time than the plagioclase, and that the iron ores do not usually separate first. It is often noticeable in basic vitrophyres that there are no iron ores, and this is also true of some basic effusives. Attention was called to it by Teall [67] in the case of some basalts from Franz Josef Land, in which the iron ores solidified late.

The interstitial character of the iron ores in gabbro has been noted in the rocks of Skye [68] where the silicate grains are outlined by narrow bands of iron ore. There are numerous references to the late separation of magnetite from synthetic silicate melts. Reiter [69] found that in melts of quite varying composition, the iron ores separate at two stages, one before augite and after olivine and the other after the augite. Washington [70] has mentioned the concentration of the dark constituents of a basaltic rock in the glass. In a later paper [71] he points out that some of the dark constituents must be in the glass in a rock as acidic as a hyalodacite. "Instances are accumulating of rocks in which much of the pyroxene belongs to the final stage crystallization or is occult in the glass and this is true also of magnetite, contrary to the well-known dictum of Rosenbusch." Sufficient evidence has been presented to show that the iron ores and proxene may crystallize from a magma at a sufficiently late stage to yield a restmagma containing a concentration of iron ores and pyroxene.

Vogt [72] has also noted that in anorthosites the pyroxene is invariably interstitial to the plagioclase.

[66] Fouqué and Lévy, "Synthése des Mineraux et des Roches," pp. 231–400, Paris, 1882.

[67] Newton, E. T., and Teall, J. J. H., "Notes on a Collection of Rocks and Fossils from Franz Josef Land," *Quart. Jour. Geol. Soc.*, 53, pp. 487–488, London, 1897.

[68] Geikie, A., and Teall, J. J. H., "Banded Structure of Some Tertiary Gabbros," *Quart. Jour. Geol. Soc.*, 50, p. 652, 1894.

[69] Reiter, H. H., "Experimentelle Studien an Silikatschmelzen" *Neues Jahrb. f. Min.*, Beil. Bd. 22, pp. 206–214, 1906.

[70] Washington, H. S., "Deccan Traps and Other Plateau Basalts," Geol. Soc. Amer. Bull., 33, pp. 772–773, 1922.

[71] Washington, H. S., Geol. Soc. Amer. Bull., 37, p. 383, 1926.

[72] Vogt, J. H. L., "Magmatic Differentiation of Igneous Rocks," *Jour. Geol.*, 29, p. 438, 1921.

The markedly interstitial character of the ore minerals suggests that they may be molten until late in the magmatic history of the rock, even after the pyroxene has crystallized.

Filtration Differentiation.—Filtration differentiation may be advanced as a possible hypothesis to account for the concentration of the ore bodies. Other explanations may be possible, but to the writer, this seems to explain best the observed facts.

If one admits that pyroxene and iron ore or iron ore alone may form a restmagma, it is comparatively simple to imagine a process that will account for the ore bodies. If by some means a separation of the solid and liquid phase can take place from this magma at the proper stage, there would result a differentiate consisting of anorthosite, and pyroxene and iron ore (or iron ore alone) Such a separation might take place in three ways: the liquid material could drain out, be driven out by gas pressure, or be pressed out. Filter-pressing seems the most probable mechanism, since the anorthosite shows abundant evidence of movement. The idea of filter-pressing is not new: Darwin considered it a possible process of differentiation. As far as the writer knows Stevens [73] was the first to suggest it to account for ore deposits. His idea of the mechanism may be gained from the following quotation: "As crystallization proceeds, however, a stage is reached when the magma becomes plastic and no longer obeys the laws of a liquid. The interstices will then contain something under 50 per cent. of fluid, and, as long as the stresses in the mass of the plastoid are all of a fluid or normal character, no segregation will take place; but lateral or shearing stresses, if sufficiently great, will tend to induce a redistribution of the fluid." Bowen has recently advocated the process as one of the most effective methods for producing the differentiation of igneous rocks, and Mead [74] has discussed some of the mechanics of the process.

The granulation of the plagioclase described by Adams, Cushing, Miller, and Bowen is evidence of movement in the anortho-

[73] Stevens, Blamey, "The Relation of Rock Segregation to Ore Deposition," *Eng. and Min. Jour.*, 76, p. 574, 1903.

[74] Mead, W. J., "The Geologic Rôle of Dilatancy," *Jour. Geol.*, 33, pp. 696–697, 1925.

site, and perhaps of filter pressing. It has usually been described as a protoclastic texture,[75] although as a rule on rather scanty evidence. Reaction rims produced in the anorthosite between isolated iron ore and granulated plagioclase are not fractured, indicating that they were formed after the solidification of the plagioclase and before that of the iron ore. Of course, as might be expected, in places the last crystallizing constituents have undergone granulation along with the plagioclase. In other words, a movement that causes protoclasis in one part of the anorthosite body may produce cataclasis in another. In the anorthosites the larger part of the foliation is marginal and it is noticeable that the ore bodies are usually not far from the margins of the masses. The extent of the movement is probably best shown by a quotation from Mawdsley,[76] "A marked feature of the contact between the anorthosite and the granite-diorite batholith is the foliated zone which follows the contact. The anorthosite is foliated over a width of 1,000–3,000 feet. . . . Outside this zone, the anorthosite is foliated only in a few places in the central part of the stock-like body." If this foliation were developed before the consolidation of the iron ore, the iron ore would have been pressed out, and an iron ore concentration would thereby result.

Localization of the Iron Ore Bodies.—The movement within the anorthosite tending to produce protoclasis along the margins would cause the liquid part of the magma to migrate to loci of lower pressure and there crystallize. It might not move out away from the anorthosite for two reasons. In the first place it would have to cross a zone of intense shearing where the pressures would be higher, and in the second place the country rock would be cooler than the anorthosite and therefore the restmagma would freeze on intruding it and block the channel ways. The logical place for it to be intruded then, is in the hot part of the anorthosite not far from the margin along which movement is taking place. Away from the margin the anorthosite is rigid and would

[75] Miller, W. J., "Features of a Body of Anorthosite Gabbro in Northern New York," *Jour. Geol.*, 29, p. 37, 1921.

[76] Mawdsley, J. B., "St. Urbain Area, Charlevoix District, Quebec," Geol. Surv. Can. Mem., 152, p. 29.

be capable of carrying the stress and so give loci of lower pressure into which the ore might migrate. Any zone of pronounced shearing in the central part of the anorthosite might form a channel and locus of deposition for the ore. As previously mentioned, there does seem to be a tendency for the ore bodies to be exposed along lines of later faulting. The occurrence may be purely fortuitous or it is possible that old lines of weakness may have been reopened by later movement. The filter-pressing hypothesis accounts for: the absence of chilled margins of the ore against the country rock; the intimate association of the ore bodies with the anorthosite; the shape of the deposits; and the location of the deposits not far from the margins of the anorthosite masses rather than at the very center. Similarly, if filter-pressing took place earlier in the sequence of crystallization of the anorthosite, a magma containing pyroxene, plagioclase, and iron ore would result. On injection and solidification this restmagma would form ore bodies resembling the Coulomb or some of the gabbro dikes cutting the anorthosite near Lake Sanford.

The principal difficulty in the acceptance of the above hypothesis is that high temperatures would probably be necessary to keep the iron ores and spinel molten. Magnetite [77] melts at 1538°.[78] Ilmenite's melting point is not known, but Vogt has estimated it as 1450°. The melting point of hematite is a little higher than that of magnetite, according to Ruff and Goecke. The melting point of hercynite is not known, so that it is virtually impossible to ascertain the temperature of a melt that would solidify to give magnetite, ilmenite, and spinel, or ilmenite, hematite, and spinel. The effect of volatiles is unknown. The geological evidence previously mentioned is overwhelmingly in favor of the ore having been molten and having contained only a moderate amount of mineralizers.

[77] Ruff and Goecke, *Zeitschr. f. angew. Chem.*, 24, 1459, 1911.

[78] 1550°, according to Ruer and Nakamoto (*Rec. d. Trav. chim. Pays Bas*), 42, pp. 667–682, 1923.

Other Occurrences.

It is probable that a large number of ilmenite and titaniferous magnetite deposits in anorthosite belong to the discordant intrusive type. It is unnecessary to treat of these deposits in detail because of the well known and adequate summaries by Vogt [79] and Kemp.[80] From their descriptions it is clear that some are not injected but that they are concentrations in place. In the majority of the Canadian deposits in anorthosite, described by Robinson, the ore bodies appear to have been injected. In most American localities where the ore occurs in anorthosite it appears to be injected. The deposit of Iron Mountain, Wyoming,[81] consisting of ilmenite, magnetite, spinel, olivine, and plagioclase has been injected into the anorthosite as a wide dike. In another deposit in Los Angeles County [82] the ore is in sharp contact with the country rock.

DISCORDANT BODIES IN GABBRO AND RELATED ROCKS.

Under "discordant bodies in gabbro and related rocks" are grouped those deposits that may be considered dikes, which intrude gabbro, norite, and diorite. The deposits of this group all have features in common and show a marked difference from the discordant deposits in anorthosite. The ore is generally fine-grained, and silicate minerals are present in considerable amounts.

Split Rock Mine.

Kemp [83] considers this mine, because of the topography and

[79] Vogt, J. H. L., "Bildung von Erzlagerstätten durch Differentiation-processe in basischen Eruptivmagmata," *"Zeit. für prakt. Geol.*, 1, pp. 4–11, 269–284, 1893. "Weitere Untersuchungen über die Ausscheidungen von Titaneisenerzen in basischen Eruptivgesteinen," *Zeit. für prakt. Geol.* 8, pp. 233–242, 370–382, 1900; 9, pp. 9–19, 180–186, 289–296, 1901. Beyschlag, Vogt, and Krusch, Ore Deposits (Tr. Truscott), p. 250 *et seq.*, London, 1914.

[80] Kemp, J. F., "A Brief Review of the Titaniferous Magnetites," *Columbia School of Mines Quarterly*, 20, pp. 323–356, 1899, 21, pp. 56–65, 1899.

[81] Singewald, J. T., Jr., The Titaniferous Iron Ore in the United States: U. S. Bur. of Mines Bull. 64, pp. 111–125, 1913.

[82] Mining in California, July, 1927. California State Mining Bureau Publication, p. 296.

[83] Kemp, J. F., "Geology of the Elizabethtown and Port Henry Quadrangles, N. Y.," New York State Mus. Bull. 138, p. 138, 1908.

development work, an especially favorable place for the study of the magmatic segregation type. The exposures are situated on the steep bluffs, that form the western boundary of Lake Champlain, 5¼ miles northeast of Westport, N. Y.

The country rock is a gabbro, which may be seen even megascopically, to vary considerably in composition from place to place. The ore [84] forms four bands 10–15 feet wide striking N. 80° W. but with variable dip. Three of the zones are shown on the map, but another similar zone to the southwest was not mapped. Cover prevents one from determining whether there is one zone that has been folded or whether there are four separate bodies. The manner in which the northeast zone turns over suggests folding of one continuous ore body. The ore shows a marked banding due to silicate richer and poorer zones parallel to the contacts with the gabbro.

According to Kemp [85] " no sharp transition " occurs at the contact of ore and gabbro. The writer found a well-defined and sharp contact, on one side of which is ore, and on the other gabbro. The sharpness of the contact is well shown even in thin section (Fig. 5.), and it makes difficult the determination of the age relationship of the ore body and gabbro. After detailed examination of the larger part of the exposed contact, the writer concluded that the ore body is younger than the gabbro. There is no appreciable difference visible either megascopically or microscopically in the gabbro which forms both walls of the ore body. Biotite is apparently developed in megascopic size only where the country rock is cut by the ore or by plagioclase pegmatite dikes. In some places apophyses extend from the ore body into the gabbro, but these may belong to a coarse facies of the ore body, which appears to cut the main ore body itself in some places. The field evidence indicates that the ore was injected after the country rock was in place and solid.

Petrography.—Only a general idea of the petrography of the gabbro can be given because of the variation that it exhibits. The gabbro in the vicinity of the deposit consists of labradorite, horn-

[84] In this case low grade material not at present minable.

[85] Kemp, J. F., *op. cit.*, p. 139.

blende, olivine and its alteration products, augite, iron ores, garnet, and biotite. Labradorite is the predominant constituent. It is of tabular habit and the crystals exhibit a marked parallel arrangement. They are extensively mashed and broken and appear to have been altered to a dark aggregate. However, under the high power of the microscope the nearly opaque appearance can be seen to be due to an immense number of non-opaque inclusions. Near

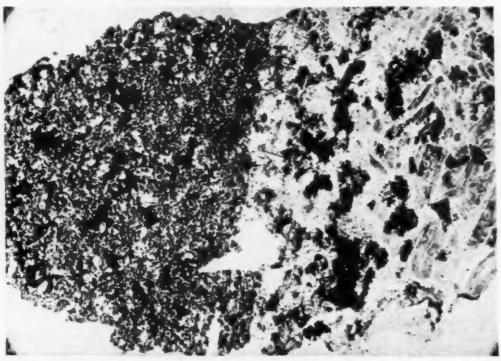
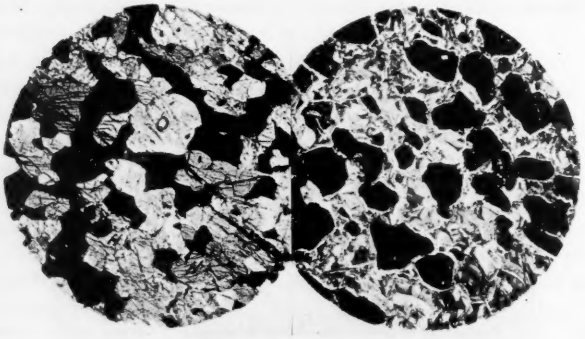


FIG. 5. Split Rock Mine. Showing the contact of the fine grained ore (left) and the coarse gabbro (right). A little of the iron ore has been introduced into the gabbro close to the contact. Note the interstitial character of the ore minerals, the sharpness of the contact between ore and gabbro, the clouded plagioclase surrounded by clear rims. × 2.

the margins of the plagioclase grains and especially where they are in contact with hornblende and garnet the swarm of inclusions disappears and is replaced by a few large individuals, usually of a light green spinel. Concurrently with the loss of the inclusions the plagioclase may become more sodic.

The reaction rims surrounding certain minerals of the gabbro are particularly interesting. In the gabbro the iron ore anhedra are invariably surrounded by reaction rims. The mineral closest to the ore is a hornblende with an extinction angle of 12° and a pleochroic formula of X-straw yellow, Y-brown, Z-dark brown,

X<Y<Z. Optically it is a basaltic hornblende. Biotite, which is almost indistinguishable from the hornblende under one nicol, is less abundant and is usually developed at a greater distance from the iron-ore core. Outside the hornblende and in contact with it is a rim of isotropic garnet free from inclusions.



6 7

FIG. 6. Split Rock Mine. Ore showing the iron ore minerals (black) interstitial to the silicate minerals, olivine (O) somewhat altered to serpentine and hornblende (H). × 13½.

FIG. 7. Chromite from Coleraine, Quebec, showing the serpentine surrounding the ore. Contrast the texture of these ores with that of Fig. 6. Crossed nicols. × 15.

Olivine is present in some of the gabbro in grains, whose elongation is parallel to that of the plagioclase. It is surrounded by a rim of colorless monoclinic pyroxene near augite. Outside the augite zone there is a rim of plagioclase free from inclusions, then a rim of garnet, the outer part of which is a graphic intergrowth of garnet and plagioclase, and a similar intergrowth of garnet and a mineral of high birefringence, which is too small to be determined. Farther from the olivine is a zone of clear plagioclase, followed by plagioclase cloudy with inclusions. The inner and outer zones of clear plagioclase, the plagioclase in the inter-

growths, and the plagioclase with the many inclusions, are usually in optical continuity. Augite occurs otherwise than as a reaction product, but it differs from the augite of the reaction rims in the presence of inclusions and in the absence of reaction minerals around it.

Thin sections of the ore show that the well-marked banding parallel to the contacts is largely mineralogical; some bands are characterized by plagioclase in considerable amounts, but in others it is almost wanting. The ore shows a well-developed sideronitic [86] texture. See Fig. 6.

Mineralogy.—The ore varies considerably in character. The larger part of it consists of an aggregate of magnetite, ilmenite, and spinel; the magnetite shows intergrown ilmenite and spinel lamellæ.

Other Adirondack deposits are like the Split Rock Mine. At the Kent Mine, Lincoln Pond, the ore appears to be as sharply bounded as at the Split Rock. The country rock is a hypersthene diorite. The titaniferous ore body is cut by magnetite of the non-titaniferous type, which is associated with an orthoclase pegmatite. The ore body at Tunnel Mountain, Elizabethtown Township is not so well exposed as the Split Rock deposit. However, it is probably also of the intrusive type. In any case thin sections of all these ores show that the iron ore minerals crystallized after the silicate minerals.

Genesis of the Discordant Bodies in Gabbro.

The discordant bodies in gabbro have a number of features in common. In the first place, the ore has a sharp rather than gradational contact with the country rock, and the ore minerals—magnetite, ilmenite, and spinel—have crystallized later than the silicates. Another noticeable feature is the variation in composition of the country rock, which includes diorite, gabbro, and the gabbroid anorthosite. The ore contains the same minerals as the

[86] Sideronitic is a term used by Duparc to describe the texture in which the iron ores are interstitial to the silicate minerals. It was first applied to the koswites in which the earliest mineral is olivine. Here it is used for the texture in which the iron ores are interstitial to the original silicate minerals.

enclosing country rock except that the proportions are different. In two of the localities the ore contains much olivine; in one of these it is common in the rock and in the other it is rare. The olivine appears to be the first mineral to have crystallized, and the iron ore the last, both in the ore and the rock. This makes it difficult to account for the deposit because it departs from Brögger's generalization that differentiation follows the order of crystallization. The hypothesis of sinking of early-formed crystals and their re-fusion at depth, which might account for the differentiation in this type, has been championed principally by Vogt.[87] He has shown that in some deposits where there is a concentration of iron ore the olivine and hypersthene tend to become iron-rich [88] in contrast to those deposits where the silicates are alone. He explains the former as due to refusion of the sunken olivine and iron ore crystals. For the deposits just described this mode of formation seems improbable because the time of crystallization of the iron ores and olivine are separated by the crystallization of all the other silicates of the rock. The rock must have been nearly solid before the iron ores separated, therefore they cannot have accumulated by crystal sinking.

It is a matter of observation that the higher the content of iron in the magma the higher the content of the iron in the minerals that will separate from it. There are a few exceptions, such as the presence of fayalite in lithophysae in rhyolites. An explanation may be framed in terms of the Mass Law. The amount of ferrous iron available seems to govern the product. In most cases of the iron-rich ore, the ferrous oxide may be disposed of in several ways: (1) It may unite with the silicate to form an orthosilicate or metasilicate, (2) it may unite with the ferric iron to form magnetite, (3) it may unite with the titanium dioxide to form ilmenite. Certain rules of occurrence may be formulated: (1) Ferrous oxide does not occur as a mineral; therefore it all must go into some other minerals. (2) The titanium dioxide gen-

[87] Vogt, J. H. L., "The Magmatic Differentiation of the Igneous Rocks," *Videnskapsselskapets Skrifter*, 1, Mat.-Naturv. Klasse 1924, no. 15, 1924.

[88] Slavik, F., "Deux roches éruptive anchi-monominérales dans le gabbro de la Bohême occidentale," *Bull. Int. de l'Acad. de Sci. de Bohême*, 1922.

erally requires enough ferrous oxide to form ilmenite because rutile is not common in the magmatic ores. (3) The ferric oxide may occur alone, or it may unite with the ferrous oxide, if there is an excess, to form magnetite. (4) In some cases, the demand of the silicates is stronger for the ferrous iron than that of the ferric oxide because hematite is often found in the segregations rich in iron silicates. In the magmas richer in iron there is usually more ferrous iron available, and for that reason ferrous oxide rich, orthosilicates such as hyalosidorite are formed instead of the more common magnesia rich olivines. Some of the magnesia that would ordinarily form the forsterite molecule may go into solid solution as spinel in the magnetite or ilmenite. If there is an excess of ferrous oxide, it may unite with the ferric oxide to form magnetite; if there is deficiency of ferrous oxide, hematite will be formed.

The above is an attempt to outline a simple explanation of what is probably a complex problem. Experimental data bearing on this problem are lacking because, as yet, the work has been confined to the pure end members of the isomorphous series. From a geological viewpoint, there are also scant data available because of the few rocks with complete petrographic and mineralographic descriptions and chemical analyses. The general condition seems to hold also for the reaction rims because in those that are formed in contact with a more acidic magma, the more iron-rich reaction minerals are found around the richer primary iron minerals.

Differentiation by sinking of phases in the magma might be tenable if the ore minerals, including spinel, could have separated as immiscible liquids early in the crystallization and remained liquid until the completion of crystallization of the silicates. However, immiscibility of iron ores in silicate-oxide melts does not seem sufficiently probable to justify its postulation.

Another hypothesis, which was entertained and rejected for the same reason, is that the gabbro and the ore were two immiscible magmas and that the ore has assumed its present relationship by reason of movement before solidification of either. Such a hypothesis would account readily for the apparently folded form of

the Split Rock deposit. It is possible that magnetite, ilmenite, and spinel are in the nature of released minerals formed at some stage in the crystallization of the magma. According to Bowen [89] magnetite is released by the pyroxene-hornblende reaction. However, the amount of magnetite, not to mention ilmenite and spinel, is too great to be accounted for by this means.

The mode of origin of the magma, which solidified to produce the ore, is unknown. It is comparatively simple to say that the ore is a differentiate of the gabbro or some other rock at depth, but the mineralogical similarity between the ore and country rock is unaccounted for. If it were not for the presence of olivine, the ore might be derived by filtering off a restmagma from the gabbro. However it is possible that the olivine may be formed in a restmagma on account of a change in the physical conditions. Du Toit [90] has described hyalosiderite as a reaction product about pyroxene in a rock showing a sideronitic texture. The olivine of the Adirondack ore bodies is not in the position of a reaction product but is found as corroded grains.

The author cannot suggest a hypothesis to account for these ore bodies. Their origin is as much a matter of doubt as that of the lamprophyric dikes, to which they show a number of similarities. They both contain a higher content of basic oxides than the rocks with which they are associated; they are both variable in mineral composition from place to place; they both contain strongly colored biotite and hornblende; and they both had a considerable content of mineralizers.

Other Deposits.

Deposits that belong to this group are probably numerous; the published descriptions are usually not adequate to place them in this class definitely.

The ore from Mine Hill, Cumberland,[91] probably belongs here,

[89] Bowen, N. L., "Reaction Principle in Petrogenesis," *Jour. Geol.*, 20, p. 183, 1922.

[90] DuToit, A. L., "Plumasite and Titaniferous Magnetite Rocks from Natal," *Proc. Geol. Soc. South Africa*, 21, pp. 53–73, 1910.

[91] Warren, C. H., and Johnson, B. L., "Contributions to the Geology of Rhode Island," *Amer. Jour. Sci.*, XXXV, p. 38, 1908.

but the gabbro is separated from the ore by an area without exposures. The deposit of Taberg in Smaland [92] is similar to the deposit at Cumberland in many respects, except that it intrudes mica schist and shows a secondary differentiation resulting in olivine hyperite and magnetite olivinite. A number of the ultrabasic rocks characterized by iron ores, such as the jacupirangites, are probably derived in the same way as these and are similarly related to the country rock. The nelsonites of Virginia [93] should also be included in this group although the country rock varies from a syenite to a gabbro. Many of the rocks, notably the gabbro nelsonites, are similar to the rocks of these deposits and show a similar sideronitic texture.

(*To be continued in next number.*)

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[92] Hogbom, A. G., "Archaean of Southern Norway," *Geol. Fören. Förh.*, Bd. 32, H. 4, p. 1041, 1910.

[93] Watson, T. L. and Tabor, T., "Geology of the Titanium and Apatite Deposits of Virginia," Virginia Geol. Surv., Bull. 3 A, 1913.

COPPER VEINS ON SUSIE ISLAND, LAKE SUPERIOR.[1]

G. M. SCHWARTZ.

INTRODUCTION.

THE mapping of the Rove slate area in Minnesota during the 1927 season involved an examination of the group of islands in Lake Superior just south of Pigeon Point (Fig. 1). The islands are part of Minnesota and with Pigeon Point form the extreme northeastern part of the state. Susie Island, which is known also as Governor's Island, is the largest of the group and is separated from Pigeon Point by less than half a mile of water

Aside from a brief note by Winchell [2] no reference to the veins on the island is found in the literature. The first exploration was a shaft sunk in the years 1882–1884 (No. 1, Fig. 1). A more extensive exploration was conducted in 1905–1907 by means of an incline and drift a short distance to the north of the original site (No. 2, Fig. 1).

The deposits yielded ore which is so striking both in hand specimens and under the microscope that it seems advisable to describe the veins in some detail. Their relation to other deposits in the Lake Superior region is also of interest.

The writer is indebted to Dr. F. F. Grout for much of the detailed mapping of the island and to Dr. W. H. Emmons for suggestions based on a visit to the island.

GEOLOGY OF SUSIE ISLAND.

A series of diabase dikes cut quartzite and slate (argillites) of the Animikie. The sediments strike N. 70° E. to N. 80° E. and dip 18° south. The dikes are at right angles to the bedding and most of them also strike about N. 75° E. They range from

[1] Published by permission of the Director of the Minnesota Geological Survey.

[2] Winchell, N. H., "The Geology of Minnesota," Final Report, vol. 4, p. 520, 1899.

20 to 50 feet wide and each shows variation. A series of four or more dikes make the ridges (80 feet high) in the north central part of the island where the veins have been prospected; another group outcrops at the south side of the island. A low swampy area between them has on the eastern side a beach gravel deposit of "red rock" granite such as outcrops on Little Brick Island

FIG. 1. Sketch Map showing geology of Susie Island.

near by; and there may be a sill of such material concealed by surface deposits on Susie Island. Winchell states that the shaft (Fig. 1) near shore reached granite before it was abandoned.

The general trend of the structure is easily traced where some dikes are well exposed, and even more positively by petrographic peculiarities of certain dikes. Two of the dikes are distinctly porphyritic in contrast with the rest, and were traced across the island with no difficulty.

The sediments are little altered by contact action near these comparatively narrow dikes; nevertheless there is some brecciation, especially where two nearly parallel dikes were intruded within a few feet of each other. Such double dikes seem to be a very characteristic structural feature of the whole district. The breccia at the incline on Susie Island is cemented with calcite and other gangue minerals.

THE COPPER-CALCITE VEINS.

Two types of mineral deposits occur. One consists of sulphides, apparently primary, in the diabase.[3] Such minerals are not conspicuous on Susie Island but are reported at a point about 100 paces northeast of the incline. The other type of mineralization is in a series of veins that cross both the dikes and the sediments in approximately vertical fractures.

The veins weather out to form grooves between the wall rocks, but being largely calcite they are conspicuously white where exposed. On the island there are few exposures of veins over 12 inches thick, but they pinch and swell locally so that larger masses may be expected, and some wider veins were reported in the drift east of the incline (No. 2, Fig. 1).

The older exploration on the south side of the east point of the island (No. 1, Fig. 1) is a shaft said to be 150 feet deep on a vein 12 inches wide. A drift to the south from the bottom of the shaft is reported to have followed a vein 7 feet wide. A drift to the north followed a narrower vein. Ore was piled on the dock for shipment, but a heavy storm wrecked the dock and scattered the ore along the beach where it is now found as peculiar white boulders that contain fairly fresh copper sulphides.

The inclined shaft of the more recent exploration was sunk from the high point of the island (No. 2, Fig. 1), on the breccia zone between two dikes. At a depth of 210 feet a drift was run 60 feet N. 70° E. to a vein that runs about N. 20° W. A few tons of ore containing 6.22 per cent. copper and a little silver were sacked for shipment before operations ceased. A con-

[3] G. M. Schwartz, "A Sulphide-diabase from Cook County, Minnesota," ECON. GEOL., vol. 20, p. 261, 1925.

spicuous vein lies 120 feet east of the incline, but it is said that the drift from the incline did not reach it.

Traces of other mineralized veins can be found at other points on the island and on the mainland. Calcite-barite veins, some of them several feet wide, are found at several places on Pigeon Point.

MINERALOGY.

The gangue minerals in the veins on Susie Island are largely calcite and quartz, but barite is locally abundant and was found in thin section intergrown with coarse calcite. The calcite shows a conspicuous dark zoning parallel to the rhombic cleavage. Polished surfaces show this to be due to numerous minute inclusions of chalcocite arranged parallel to the cleavage. Quartz and chalcedony are abundant in some thin sections, and quartz crystals line some small vugs. There is more silica in the vein material than might be suspected from the hand specimens. No other gangue minerals of importance were found.

The thin sections, as well as the polished surfaces, indicate that much of the sulphide ore is later than the calcite, but the occurrence of inclusions of chalcocite in the zoned calcite indicates the presence of copper sulphides during the deposition of the calcite. No doubt the deposition overlapped.

The ore minerals in order of abundance are: bornite, chalcocite, chalcopyrite, pyrite, covellite, and malachite.

Bornite.—Bornite is found in most of the fifty polished specimens available, and in seven it is the only abundant sulphide. The most striking occurrence is in the more or less spherical structures with chalcopyrite (Figs. 2–4). The relations shown by these two minerals are complex and difficult to explain. Similar structures for these minerals have not been described for other deposits, so far as known. The lattice-like intergrowth (Figs. 7 and 8) present in many specimens resembles the structures attributed by some investigators [4] to the breaking down of a solid solution, but the relationships of Figs. 3 and 7 show that

[4] See, for example, Van der Veen, R. W., "Mineralography and Ore Deposition," 1925, Figs. 45, 46, and 50, and page 47.

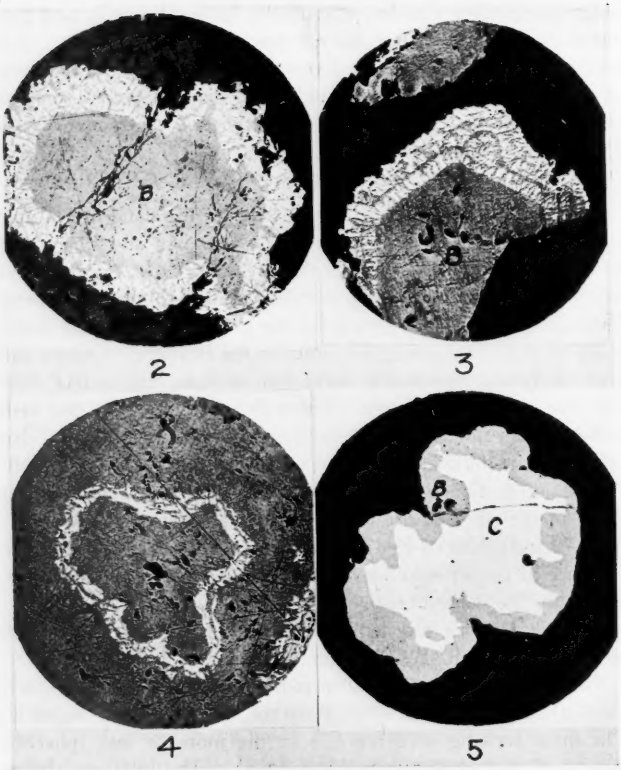

FIG. 2. Bornite (B) surrounded by a lattice-like intergrowth of bornite and chalcopyrite. The sulphides replace calcite (C). $\times 60$.

FIG. 3. Structure somewhat similar to that shown in Fig. 2. Bornite (B) with bornite-chalcopyrite (white) fringe. Probably a further stage of replacement of chalcopyrite by bornite. Black is calcite. $\times 40$.

FIG. 4. Ring of chalcopyrite surrounding bornite and surrounded by bornite. $\times 80$.

FIG. 5. A mass of chalcocite (C) surrounded by bornite (B) and the latter by calcite (Ca). The zone of bornite between calcite and chalcocite is characteristic of the ores. $\times 40$.

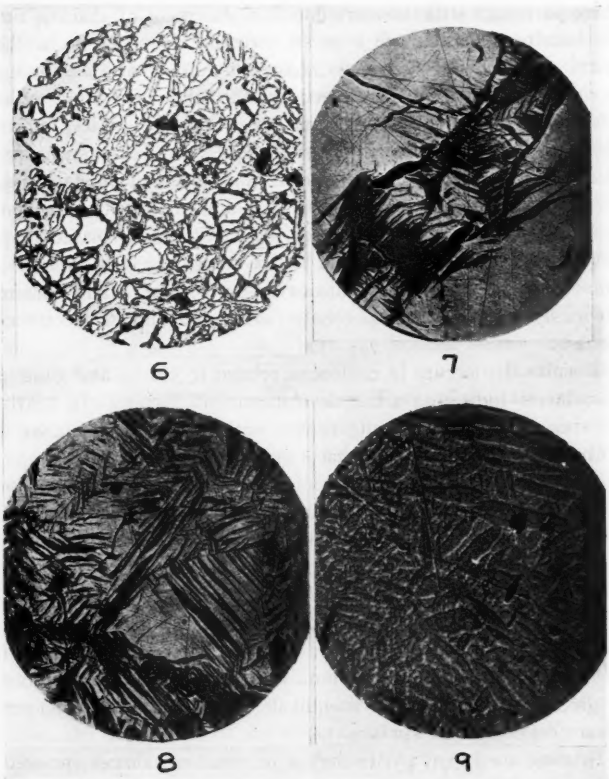

FIG. 6. Pyrite remnants in bornite. × 80.

FIG. 7. Bornite (dark) forming lattice-like intergrowth in chalcopyrite. Relation of bornite to cracks in chalcopyrite indicates replacement of chalcopyrite by bornite. × 80.

FIG. 8. Lattice intergrowth of bornite (dark) and chalcopyrite (light). This resembles structures often attributed to breaking down of a solid solution. In this case evidence from other fields shows it to be a result of replacement. × 80.

FIG. 9. Blades of bornite (dark) in chalcocite (light). This is exact duplicate of a structure produced by slow cooling of a solid solution of bornite and chalcocite. This structure is found where bornite and chalcocite seem to fade into each other. × 650.

these particular structures are due to replacement of chalcopyrite by bornite. This lattice type of structure is common in the bornite-chalcopyrite specimens from this deposit, and assumes a variety of forms. In some specimens the sulphides form a series of scallops along the gangue and there is more or less of an alternation of the two sulphides; in others bornite occurs in spherical areas of chalcopyrite as a network of minute veinlets. Fig. 2 illustrates a concentric mass of sulphide of which the center is bornite, and around the outside, chalcopyrite is replaced by a network of bornite assuming a lattice structure. Fig. 4 shows only an isolated ring of chalcopyrite in bornite. The bornite obviously replaces the chalcopyrite along crystallographic directions.[5]

Bornite also occurs in chalcocite related to cracks and gangue boundaries, indicating a late development of bornite. In nearly all specimens where bornite occurs with chalcocite it shows a preference for the calcite contacts as shown in Fig. 5.

Chalcocite.—Chalcocite occurs in a variety of relations in the ores. The most abundant occurrence is as a replacement of pyrite. Pyrite was evidently abundant as an early sulphide and has been brecciated and replaced by all the later sulphides. Chalcocite, which appears in the hand specimen to be nearly pure, is found on polished surfaces to be filled with innumerable minute remnants of pyrite. The writer estimated that in a single field of the microscope with an 8 mm. lens there are 1,200 or more fragments of pyrite. This is equivalent to 85,000 fragments per square centimeter of surface.

In some specimens pyrite-chalcocite areas are almost enclosed in bornite. The development of these seems to be somewhat as follows: pyrite, the earliest sulphide, was brecciated and replaced by copper solutions. The pyrite was directly replaced by chalcocite, but surrounding areas were filled by bornite, which may have replaced calcite. In any event the pyrite seems to have favored, in some way, the development of chalcocite.

[5] For discussion of intergrowths following crystallographic directions of chalcopyrite see Schwartz, G. M., "Intergrowths of Chalcopyrite and Cubanite," ECON. GEOL., vol. 22, pp. 44–61, 1927.

Chalcocite also occurs intimately associated with bornite, disseminated in calcite. Some specimens of chalcocite contain remnants of calcite. The pronounced zoning in the calcite, as noted above, is due to minute inclusions of chalcocite.

Much of the chalcocite shows a complete independence of visible channels, cleavage, and mineral boundaries, so that its hypogene origin seems obvious; it contains innumerable remnants of pyrite as noted above. A small amount occurs along minute cracks associated with covellite, and is evidently supergene.

One specimen of ore from the old shaft (No. 1, Fig. 1) shows with moderate magnifications an apparent gradation from chalcocite to bornite. Bornite and chalcocite are disseminated in calcite, and in areas containing both the bornite shows the usual preference for the gangue contacts. (Fig. 5.) Examination of the gradational zone at high magnifications shows a series of blades of bornite in the crystallographic directions of the chalcocite (see Fig. 9). This type of structure has been artificially produced by the slow cooling of a solid solution of bornite and chalcocite.[6] There is such a marked similarity between the natural and artificial intergrowths that a similar origin seems likely.

Chalcopyrite.—Chalcopyrite is found in a majority of specimens and was apparently the earliest copper mineral formed as in most specimens it does not replace earlier sulphides, except rarely pyrite. There is a small amount of late chalcopyrite that replaces bornite along cracks and cleavage. This is so different from the main mass of the mineral that it is undoubtedly a distinct generation, possibly supergene. Chalcopyrite is usually associated with bornite, which occurs with it as a lattice intergrowth, a network of veins, and in the scalloped and concentric structures noted under bornite.

Pyrite.—There are two types of specimens that contain abundant pyrite; one, consisting of fragments in chalcocite, has already been mentioned, and the other consists of similar fragments in bornite (Fig. 6). Much less commonly chalcopyrite

[6] Schwartz, G. M., "Experiments Bearing on Intergrowths of Bornite and Chalcocite," ECON. GEOL., vol. 23, pp. 381–397, 1928.

appears to replace pyrite. Normally there seems to be a direct replacement of pyrite by chalcocite.

Covellite.—Covellite is not abundant, but is rather widespread. A small amount is found as large grains with chalcocite in a manner indicating a primary origin, but most of it occurs as veinlets and tufts replacing other sulphides in a manner characteristic of supergene replacement. Bornite seems to yield to covellite more readily than either chalcocite or chalcopyrite.

ORDER OF FORMATION OF SULPHIDES.

It is not uncommon to find that a given deposit shows a rather uniform sequence of minerals. This might be expected in the series of small veins found on Susie Island, but there is no uniform order of formation of the copper sulphides.

Of the sulphides, pyrite is invariably the earliest. In many specimens it is directly replaced by chalcocite and no further change has taken place. More rarely pyrite is replaced by bornite or chalcopyrite, but a successive replacement of pyrite by the sequence chalcopyrite-bornite-chalcocite was not observed.

Chalcopyrite, bornite, and chalcocite were in part deposited without obvious replacement of earlier sulphides. They seem to be true primary minerals. Chalcopyrite is often replaced by bornite; and bornite by chalcopyrite, presumably supergene. Chalcocite is replaced by bornite, but strangely enough there is no clear evidence that bornite is replaced by hypogene chalcocite. The two minerals seem to be contemporaneous in several specimens. Rarely a little supergene chalcocite is developed in bornite, but covellite is much more common, although not abundant as a supergene sulphide.

CONCENTRIC, ROSETTE AND SCALLOP STRUCTURES.

Even a casual examination of the Susie Island ores brings out the peculiar concentric, rosette and scallop-like structure of the sulphides in the calcite. A few of these are illustrated in the figures accompanying this paper, but several more photographs would be necessary to convey an adequate idea of these peculiar structures. The writer has not observed similar structures in the many other copper ores studied in the laboratory, and they are

uncommon in the various papers published on the mineralography of the copper ores. These structures recall at once the ore of Cobalt of Silver Islet,[7] and of Kennecott, and it seems that the calcite gangue of all of these deposits is in some way responsible for the concentric structures. This has been suggested by Guild and perhaps his ideas may be applied to the Susie Island ores. Guild's conclusion is as follows:[8] "The peculiar concentric structure seen in the cobalt-nickel minerals is believed to be due to the habit of the early mineral, smaltite, to replace calcite in the form of concentric shells. The later minerals replacing the remainder of the calcite inside the shells complete the structure. The spaces between the shells are sometimes filled (by replacement of calcite) with the earlier mineral smaltite, less often by the later mineral niccolite."

Lindgren[9] has attributed the colloform structure to gel-replacement of a crystalline carbonate filling. He believes that the metals at Cobalt were introduced as chlorides mixed with arsenic sulphide and hydrogen sulphides or alkaline sulphides. The solutions were neutralized, and sulphides, together with sulphur and arsenic, were precipitated as a complex gel. The complex gel was amost immediately transformed into crystalloids, resulting in the mixture of minerals now found in these deposits. This seems to be the logical explanation of the formation of these peculiar structures.

RELATION TO OTHER DEPOSITS.

The occurrence of veins of copper sulphides on Susie Island is significant because they are found in a province characterized by quite different types of deposits.[10] The Lake Superior region,

[7] Bastin, E. S., ECON. GEOL., vol. 12, pp. 220–237, 1917. Guild, F. N., ECON. GEOL., vol. 12, pp. 297–353, 1917. Bastin, E. S., U. S. Geol. Survey Bull. 735, pp. 131–154, 1922. Chadbourn, C., ECON. GEOL., vol. 18, pp. 77–83, 1923. Bastin, E. S., ECON. GEOL., vol. 20, pp. 1–24, 1925. Todd, E. M., Ontario Dept. Mines, 35th Ann. Rept., vol. 35, pt. III, pp. 62–78, 1926. Bateman, A. M., and McLaughlin, D. H., "Geology and Ore Deposits of Kennecott, Alaska," ECON. GEOL., vol. 15, pp. 1–80, 1920, and especially Plate IV.

[8] Guild, F. N., *op. cit.*, p. 339.

[9] Lindgren, W., "Metasomatism," *Bull. Geol. Soc. Amer.*, vol. 36, pp. 247–262, 1925.

[10] Lindgren, W., "Metallogenetic Epochs," ECON. GEOL., vol. 4, pp. 409–420,

aside from its sedimentary iron deposits, is characterized by deposits of native copper in which arsenides are not uncommon, but sulphides are comparatively rare. The native copper deposits are found in Keweenawan conglomerates and basic flows, and wherever the Keweenawan basic flows are exposed, around Lake Superior at least, small amounts of native copper are usually to be found. The Susie Island deposits are associated with basic dikes presumably of Keweenawan age and flows of undoubted Keweenawan age are exposed on Lucille Island a quarter of a mile to the south of Susie Island. In short, the location suggests relationships to the deposits of Keweenaw Point, but they have no other important features in common.

Small deposits of chalcopyrite, with pyrrhotite and pentlandite have been found on the mainland near by, but these are of a still different type,[11] and mineralogically resemble more closely the Sudbury deposits.

Texturally the Susie Island ores show striking analogies to the deposits of Silver Islet, and of Cobalt, Ontario. The peculiar concentric, rosette, branching and dendritic structure of the ore minerals in the calcite gangue have been described and illustrated in the papers cited. The similarity of the textures of the Susie Island ores is obvious. Mineralogically and chemically, however, the deposits have little in common except the calcite. Cobalt and nickel arsenides and native silver are characteristic of the deposits at Cobalt; galena, sphalerite, niccolite, and native silver are abundant at Silver Islet; chalcocite and bornite are characteristic at Susie Island. An assay for arsenic in the Susie Island area failed to show a trace. Silver assayed 0.16 ounces per ton. Copper sulphides are unimportant at either Cobalt or Silver Islet. The only mineral common to all three deposits is calcite. This indicates, as suggested above, that the structure of the ore minerals is in some manner controlled by the structure of the calcite.

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1909; "Mineral Deposits," 3d edition, p. 1000, 1928. Emmons, W. H., "Principles of Economic Geology," p. 209, 1918.

[11] Schwartz, G. M., "A Sulphide Diabase from Cook County, Minnesota," ECON. GEOL., vol. 20, pp. 201–265, 1925.

SOME GEOLOGICAL CONSEQUENCES OF THE SELECTIVE ADSORPTION OF WATER AND HYDROCARBONS BY SILICA AND SILICATES.[1]

P. G. NUTTING.

GEOLOGICAL problems related to the origin and accumulation of petroleum and of asphalt beds as well as industrial problems concerning petroleum recovery, the filtration of oil and the flotation of ores, are intimately connected with selective adsorption. A preliminary report of investigations in this field was published in this journal[2] in 1926. Since then much further work has been done. Reports on the chemical and technical aspects of this investigation have been published and are appearing elsewhere, but some geological relations remain to be pointed out. If the results appear incomplete and fragmentary, it is largely because of the almost insuperable task of isolating and identifying the innumerable hydrocarbons filterable from petroleum by silicates, many of which are unstable when isolated and obtainable only in minute quantities.

Silica and most silicates, many oxides of the metals and many salts as well as solids in general, adsorb thin films of air and other gases, water vapor, liquid water, salts in solution, hydrocarbons and other fluids to which they may be exposed. These films vary from a few molecules to hundreds of molecules deep or from 0.4×10^{-8} cm. up to a micron (10^{-4} cm.) in thickness. Whether or not two or more substances may be adsorbed on the same surface at the same time, either mixed or superposed, we have but little knowledge. The adsorption may be mere physical adhesion (wetting) or a real surface reaction with the formation of a new compound arrested by insolubility.

[1] Published by permission of the Director, U. S. Geological Survey.

[2] Nutting, P. G., "Geochemical Relations between Petroleum, Silica and Water," ECON. GEOL., vol. 21, 234–242, May, 1926.

This thin film in itself may be of little consequence except in a few cases, but the displacement of one film by another and selective adsorption in general play important rôles in nature and in industry. The results are familiar enough but the explanation difficult.

Filtering earths are commonly used to remove highly colored constituents from oils. Their action is not one of straining, for a quartz sand filters as well in proportion to its surface area as a fine filtering clay or a porous silica gel. The more highly colored portions are adsorbed and held by the filter, while the less strongly adsorbed colorless ones pass through. A well dried silica or silicate filter of sufficient depth filters petroleum to a water white, one in equilibrium with ordinary humidities only to yellow, orange or red, while one that has been sintered filters scarcely at all.

The explanation offered in the writer's previous paper and elsewhere is that driving off moisture (by heating) removes terminal H and OH radicals as water, leaving a surface having open bonds ready to attack unsaturated and other active colored hydrocarbons. Pure kaolinite ($H_4Al_2Si_2O_9$) does not filter because it has no terminal OH water. Water leaves it only on raising the temperature above 500° C. The montmorillonite group of clays (classification of C. S. Ross), the bentonites, are but poor filters because but part of their OH is terminal, removable by heating. Green sand, serpentine and the hydromicas make good filters after acid treatment because the acid changes the terminal OK, ONa and O_2Mg radicals to OH removable by moderate heating (200° C.). It is now quite feasible to tell good filtering clays from their chemical analyses alone.

When a filter is moist, with its terminal H and OH in place over the surface, evidently only hydrocarbon or other radicals stronger than these can be adsorbed and displace them from their favored positions. The yellow, orange and red constituents of petroleum are unable to do this and are passed by a moist filter, but the stronger brown or black components are adsorbed and held in a thin tarry coating not removable by ordinary solvents.

Some pure quartz oil sand (Tensleep, Oregon Basin, Wyoming,

3850 feet) was at hand on which the coating was just visible after thorough washing in pure gasoline and CCl_4. Repeated determinations of its thickness (by weighing and removal with chromic acid) gave 80×10^{-6} cm. This is twenty times the thickness (4×10^{-6} cm.) of the water film on quartz in equilibrium with ordinary room humidities, which is roughly 100 molecules deep. Filtering an asphalt base petroleum through clean sand left a film that could not be washed off, almost as thick (0.3 to 0.6 micron) as that found on the Tensleep sand.

When a base is attached to or in combination with an acid radical (such as silica) the obvious agent for its removal is a stronger base either ionized as a free radical or combined with a still weaker acid and then hydrolyzed. This is the basis of the method of recovery of spent petroleum with sodium carbonate solutions. The stronger base displaces the absorbed alkyl hydrocarbons adsorbed on the sand. Tests show that even a firmly absorbed tarry film is removed—much as a photographic negative is "lifted" from a plate by dilute hydrofluoric acid—only the process is much slower, for the soda has to diffuse through the film.

The water constituents H and OH are but very weak radicals as are also the alkyl and acyl radicals of the hydrocarbons but the latter are partly weaker and partly stronger than the former. Hence plain water can drive the weaker hydrocarbons (colorless paraffins and olefins for the most part) from oil-saturated sand, but if a tarry film has been formed, soda is required. But a grain of silica or silicate once coated with a tarry film becomes thereafter in effect a carbon grain and prefers oil to water. The thin film, in other words, has changed it from a hydrophilic to a hydrophobic solid—a complete inversion in nature and properties.

The question has been frequently raised, How could petroleum displace water in wet sand? The answer is simple. The constituents of petroleum stronger than OH first coat the sand grains, which then prefer oil to water and will even collect oil droplets carried along in suspension in water. A light colorless hydrocarbon oil, consisting of pentane, octane, benzol and the like, could not displace water from wet sand.

The ideal flotation oil is one just a little weaker than OH so that it will float the hydrophobic particles of metallic sulphide ore but not the hydrophilic silica and silicate gangue. Common practice is to use a strong flotation oil weakened with soda until it will not float gangue—a rather difficult adjustment—or else a vegetable oil containing OH.

Trinidad asphalt contains uniformly 35.5 per cent. of silicate matter in the form of clay and fine earth and 10 per cent water of hydration. If this mineral matter is partly a filtering earth as defined above, then it is not difficult to account for the formation by the upward percolation of asphalt base petroleum. With the clay originally wet, only the more strongly basic tars would be strongly adsorbed, carrying the clay and water with them in definite proportions.

The interlocking of adjacent adsorbed films is apparently what gives paving asphalt and many roofing materials their firm structure. By heating and thus driving off OH from both a filtering earth and a pitch and then combining them, the writer has produced a material almost as hard as brick when cold, though soft while hot.

Vegetable and animal tissues in intimate contact with finely divided silica and silicates, and some oxides (particularly those of iron and aluminum) are subject to strong disintegrating effects due to the tendency to removal of H and OH and of alkyl and acyl hydrocarbons and reversal from hydrophilic to hydrophobic character. Even when coated with basic hydrocarbons, the grains are subject to cleaning action by solutions of the stronger inorganic bases. The products formed are soluble, however, and tend to hydrolyze. The net result then is that the mineral matter may act as a weak but very active catalyst. The disintegrating effects would be enhanced somewhat by pressure and very greatly by shear in the structure. Selective reversible adsorption doubtless plays an important rôle in soils in the preparation of plant food. Much of the decomposition and recombination of organic matter in contact with silica, heretofore tentatively attributed to bacterial action, may be due to alternating selective adsorption by

silicates in the cycle (1) surface hydration, (2) dehydration by organic bases that are weak but still stronger than OH, (3) displacement of these organic bases by still stronger inorganic bases and (4) and (1) solution of these inorganic bases or alkaline silicates, restoring the original hydrated condition, the small net energy required coming from heat of solution in (4). The possibility of such cyclic changes in the case of fluids passing through porous solids appears well worth consideration.

Summary.—Water, adsorbed on silica and silicates as H and OH ions, may be displaced by the stronger alkyl hydrocarbons but not by the weaker lighter and colorless ones.

Petroleum may enter and fill sands previously filled with water or water solutions provided it contains basic constituents stronger than OH.

Changing the film adsorbed on silicates from OH to alkyl hydrocarbons reverses the character of the silicate from hydrophilic to hydrophobic.

The most efficient flotation oils for sulphide ores are those composed of hydrocarbons just a little weaker than hydroxyl (OH) ions.

The Trinidad asphalt deposit is such as would be expected from an asphalt base petroleum percolating upward through a fine grained wet silica or silicate of the nature of a filtering earth (one provided with terminal hydroxyl radicals).

Silica and silicates of the filtering type may serve as active catalysts in the breakdown of animal and vegetable tissues. A homogeneous shear will assist this disintegrating action.

In the preparation of plant food by soils, selective adsorption, in cycles determined by relative abundance of water and oxygen, may play an important part.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.

ELECTRICAL CONDUCTIVITY AND POLISHED MINERAL SURFACES.

ROGER D. HARVEY.

Introduction.

An important policy of the Laboratory of Economic Geology, Harvard University, in recent years has been the extending and perfecting of means for identifying opaque minerals in polished section.[1] There remained to be considered, among other characteristics, the value of electrical conductivity as a factor in the identification of opaque minerals. This field the writer has been investigating in the past two years and the results are given in the following pages.

The writer had only secondary interest in the conductivity of opaque minerals in lumps or fragments of macroscopic size. The scope of the investigation was narrowed to satisfy two conditions: (1) that the mineral be polished in one plane, (2) that the test be made under the microscope.

Previous Work in this Field.—Considerable work has been done on the electrical conductivity of minerals by European investigators, of whom the more important are (chronologically arranged): Wartmann,[2] Braun,[3] Dufet,[4] Baeckstrom,[5] Abt,[6]

[1] Talmage, S. B., Econ. Geol., vol. 20, pp. 168–180, 1925. Murdoch, J., "Microscopical Determination of the Opaque Minerals," New York, 1916. Davy and Farnham, "Microscopic Examination of the Ore Minerals," New York, 1920. McKinstry, H. E., Econ. Geol., vol. 22, p. 669, 1927. Short, M. N., unpublished notes. Vanderwilt, J. W., Econ. Geol., vol. 23, pp. 292–316, 1928.

[2] Wartmann, Elie, *Mem. de la Soc. d'hist. natur. de Geneva*, 13, p. 199, 1852.

[3] Braun, F., *Poggendorff Annalen*, 153, p. 556, 1874.

[4] Dufet, F., *Compte rendu*, 81, p. 628, 1875.

[5] Baeckstrom, H., Oefver, *Vet. Acad. Foerh.*, Stockholm, 45, p. 533, 1888; 51, p. 545, 1894.

[6] Abt, A., *Wiedemann Annalen d. Phy.*, 62, p. 474, 1897.

Beijerinck,[7] Streintz,[8] Césaro,[9] Boedlander and Idaszewski,[10] Moench,[11] Koenigsberger and Reichenheim,[12] Baedeker,[13] Tubandt and his pupils,[14] and A. Joffé.[15] These students in all cases used specimens of macroscopic size, whose dimensions were accurately known. The shape commonly conformed to that of the prism, cylinder or plate, from which bodies the specific resistance was easily calculable.[16] Streintz and Moench used compressed powders, the resistance being determined when the mineral grains in a cylindrical chamber were under high pressure. The mineral was as homogeneous as possible, unusually so in the case of the compressed powders. Resistance was commonly measured by some form of Wheatstone-bridge, or by a combination of instruments which read both voltage and amperage. Contact resistance, that is, the resistance encountered by the current in passing from the tip of the electrode to the investigated mineral, and the reverse, was largely or completely eliminated by clamping the mineral tightly against platinum, silver or lead terminals, or by immersing the ends of the specimen in mercury and conducting the current to the latter. Streintz used a Nernst-modified Wheatstone-bridge, by which the contact resistance of each terminal was evaluated and their sum subtracted from the total resistance. The current commonly was alternating, but in certain cases direct.

Numerous Americans also have studied the conductivity of the opaque minerals. In this field one finds, among others, the names

[7] Beijerinck, F., *Jahr. f. Min.*, Beil. Band, 11, p. 403, 1897–98

[8] Streintz, F., *Ann. d. Phy.*, 3, p. 1, 1900; 9, p. 854, 1902.

[9] Césaro, G., *Bull. de la Classe de Soc. de l'Acad. Roy. de Belg.*, p. 115, 1904.

[10] Boedlander, G., and Idaszewski, K. S., *Zeits. f. Elektroch.*, 11, p. 161, 1905.

[11] Moench, W., *Jahr. f. Min.*, Beil. Band, 20 p. 365, 1905.

[12] Koenigsberger, J., and Reichenheim, O., *Jahr. f. Min.*, 11, p. 20, 1906.

[13] Baedeker, K., *Ann. d. Phy.*, 22, p. 749, 1907.

[14] Tubandt, C., Eggert, S., Schibbe, G., *Zeits. f. Anorg. Chem. u. Allge. Chem.*, 117, p. 1, 1921.

[15] Joffé, A., *Ann. d. Phy.*, 72 p. 461, 1923.

of Pierce,[17] Hayes,[18] Coblentz,[19] Davy and Farnham,[20] Waterman, [21] and Kerr and Cabeen.[22] Of these, Farnham, and Kerr and Cabeen alone appear to have aimed to use varying conductivity as a tool for microscopically distinguishing unknown minerals in polished section. Farnham's apparatus was ideally simple. It consisted of needle terminals attached to holders held in either hand, and connected to a circuit consisting of two dry-cells and an ammeter (reading, however, not in standard units or amperes). Kerr and Cabeen's device was more elaborate and satisfactory. Conductivity was determined by the number of electric bulbs lighted by the current after passing through the mineral, or in certain cases by the amount of deflection which the needle of a milliammeter suffered when placed in the circuit. On the basis of behavior they divided the more important opaque minerals into six classes.

Below are enumerated the principal results and findings of many observers in this field, notably those using macroscopic specimens.

1. Some 100 opaque minerals were studied, or about half of the known species. Practically all opaque minerals that contribute notably to the world's metal were studied by more than one individual, the amount of attention received being more or less proportionate to the commercial importance of the species.

2. The conductivity or resistivity of a natural opaque mineral is not a constant, but covers a range whose limits are as yet unknown. Abt [23] found that certain magnetite from Moravitza conducted 695 times better than other magnetite from the same

[16] The specific resistance is the resistance of a body 1 cm. long with a cross-section of 1 square centimeter.

[17] Pierce, G. W., *Phys. Rev., 1st Ser.*, 25, p. 31, 1907; 28, p. 153, 1909; 29, p. 487, 1909.

[18] Hayes, H. V., *Proc. Amer. Acad.*, 46, p. 615, 1910–1911.

[19] Coblentz, W. W., Bur. of Stand. Bull. 14, p. 322, 1917–1918.

[20] Davy and Farnham, Microscopic Examination of Opaque Minerals, pp. 8 and 123, New York, 1920.

[21] Waterman, A. T., *Phys. Rev.*, 2d Ser., 21, p. 540, 1923.

[22] Kerr, P. F., and Cabeen, C. K., ECON. GEOL., 20, p. 729, 1925.

[23] Abt, A., *op. cit.*, p. 477.

locality. Beijerinck,[24] who has made the most extensive observations of electrical conductivity of all experimentors, has noted cassiterite that showed no conductivity when colorless, but good conductivity when black. Hematite has been proven to show variations of at least 7500 fold. On examining the findings of the observers, one only rarely finds agreement in the results; frequently the discrepancies are enormous.

3. There is evidence to show that the poor conductors possess greater conductivity ranges than the good.

4. The principal cause of variation in conductivity for a given species is the presence of foreign inclusions or chemical impurities.

5. Other causes of variation in conductivity are non-uniform crystallographic orientation, variable temperature, fracturing, destruction of the crystal-lattice (by compression, torsion, etc.), and exposure to light (*e.g.*, in stibnite).

6. All or nearly all binary compounds possess negative temperature-coefficients. On the other hand, for the native metals the coefficient is commonly positive. The value of this coefficient is not constant; it may disappear over certain ranges or may alter in sign.

7. Conduction in opaque minerals is regarded as metallic (free electrons) with the exception of two and possibly more minerals, namely, argentite and chalcocite (according to most observers). Argentite apparently always conducts electrolytically, that is, by dissociation. Acanthite (according to the old nomenclature) conducts at the same time both electrolytically and metallically. By many students orthorhombic chalcocite is believed to behave before the electric current as a solid electrolyte. Concerning the nature of conduction in isometric chalcocite there is some question. Other metallic compounds may prove to conduct electrolytically.

8. Koenigsberger and Reichenheim have shown that for pyrite, specularite, and marcasite, there is extremely little difference in the ohm-resistance at moderately high temperature, whether direct

[24] Beijerinck, F., *op. cit.*

or alternating current is used. Since most opaque minerals seem to conduct metallically, it is assumed that the nature of the current is immaterial. This of course does not apply to solid electrolytes which polarize with direct current.

9. According to Waterman,[25] for certain molybdenite, Ohm's law[26] does not hold. The departure, while not great, is detectable. The assumption has been made in most investigations, however, that the law does hold, at least for relatively crude work, and that at constant temperature the voltage rises proportionally with the amperage.

10. Insufficient attention to the element of contact resistance has vitiated the accuracy of many results, and, until it is eliminated, the value read for internal resistance will be somewhat too high.

Experiments.

Factors in Choice of Apparatus.—The limitation of the study to plane polished surfaces necessitated the choice of special devices for applying the current to the desired spot. A body of needle-like form[27] was found most satisfactory. By its use a very small portion of the field can be covered, and the current can be made to flow through a sufficiently minute linear distance. If composed of proper material, a considerable weight can be applied (thus reducing contact resistance) without bending the tips even when the needle is inclined to the polished surface. Moreover, given a suitable metal, resistance to corrosion by heat-effects and chemical action will be reduced or obviated. The smaller the needle-tip, of course the greater will be the electrical resistance, but, unless the tip is reduced to very minute dimensions, this factor should not be embarrassing.

The application of electrical current to a polished plane-surface involves difficulties not encountered in using specimens of macroscopic size. In the latter, the space between the terminals is

[25] Waterman, A. T., *op. cit.*, p. 540.

[26] $\frac{\text{electromotive force}}{\text{current}} = \text{constant.}$

[27] This was the type of terminal used both by Farnham and by Kerr and Cabeen.

occupied by the mineral under examination, and the current passes with equal ease in all directions on entering the mineral. In the present method, allowing for no depression of the tips in the specimen, the space between terminals is occupied by the contact surface of two media, air and mineral. Since no conduction takes place through air, the electrical lines of force tend to be concentrated in the conducting mineral with the result that internal resistance is increased. The nature of the path of the electrical current, when applied to one plane surface, has not been, so far as the writer knows, the subject of investigation. His own observations seem to show that the component of the path perpendicular to the surface is much greater than the component parallel thereto. The effect seems to be to considerably increase the vertical component over that found in the case of current application at the ends of opposite faces of mineral specimens.

Another factor involved is the influence of physical or chemical alteration of the mineral itself. A part of the current passes directly, or with slight deviation, from one terminal to the other. In so far as it follows this path, it traverses a medium of somewhat altered or distorted crystallographic structure. Some physical alteration of the mineral has been brought about by the original breaking out of the specimen, and, more, by the subsequent grinding and polishing. Chemical alteration may result from exposure to the atmosphere and possibly in certain cases from heating effects.

It may be objected that such influences will be too small to cause notable variations in the electrical resistance of a mineral. But some at least of the factors that produce variations operate out of all proportion to the quantity of the factor. Beijerinck, for instance, showed clearly that a small percentage of quartz, or some form of SiO_2, in cassiterite vastly increased the resistance of the latter. A more familiar example is the effect of a small amount of arsenic on the conductivity of copper.[28]

Neither in the work of Farnham, nor in that of Kerr and

[28] In producing this effect the nature of occurrence of the impurity (physical admixture or alloy) appears to be immaterial.

Cabeen, could the contact resistance be maintained constant. The latter noted the conductivity at the moment of maximum pressure on the terminals. Likewise, in the case of the earlier experimentors, a terminal was held in either hand, and obviously the pressure could not possibly be equal. On the other hand, could the amount of surface at the tip of the terminal and its pressure on the surface be maintained constant, then the variability of the contact resistance ought to be considerably reduced, at least for a given specimen, or even a mineral species. Fixed inclination of an unbending needle as a terminal should insure the former, and constant weight on that needle the latter.

In this connection the writer has discovered evidence that conflicts with the findings of Farnham in regard to the relative importance of contact resistance compared with internal resistance. Farnham interprets the rough constancy of his readings, when the distance between the terminals is varied, to indicate that the contact is much greater than the internal resistance The writer also held this view prior to using measuring instruments, one of which gave the internal resistance only, while the other gave the combined internal and contact resistance. A comparison of results with the two instruments showed that the cause of the frequent constancy of readings with variable distance between terminals, was due more to the vertical (with respect to the polished surface) component and the horizontal component (perpendicular to the line between terminals) of the combined internal resistance than that of contact. For all but excellent conductors it can be concluded that contact resistance is greatly exceeded by the two components of the internal.

The effect of resistance in a conductor is of course to produce temperature elevation. Now, as has been noted, previous experimenters have shown that in many opaque minerals the temperature-coefficient is negative, *i.e.*, the resistance decreases with rise of temperature. The effect of electrical resistance is then to diminish the ohm-value below what it would be at room-temperature. This cannot be avoided, nor is it practicable to read the temperature of the observed mineral and from a temperature-

resistance curve compute the value at room-temperature. The more feasible course will be to maintain the current at as low a density as is consistent with accurate reading of the instruments.

It will be assumed that the discovery by Koenigsberger and Reichenheim of the identity of resistance for direct and alternating current in the minerals specularite, pyrite, and marcasite, applies to all members of the opaque-mineral kingdom with the exception of the electrolytes. The writer felt justified, therefore, in using direct current in this study, particularly as it necessitates instruments that are simple and inexpensive. Direct current, however, is not adapted to the determination of the resistance of argentite, and any other electrolytes. The values noted for these will be higher than if an alternating current were used.

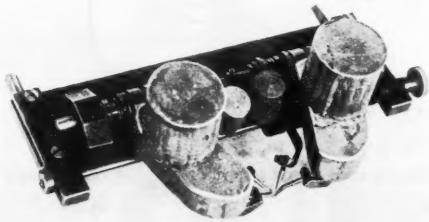


FIG. 1. 4-terminal tester in detail.

Types of Circuit and Testers Designed.—After considerable preliminary experimentation two types of electrical circuit, each with its own tester, were finally adopted. One, the more valuable in the writer's view, was the potentiometer with 4-terminal tester. The other was the Wheatstone-bridge with a 2-terminal tester. Figs. 1–4 show both testers and electrical apparatus.

The 4-terminal Tester.—Referring to Fig. 1, the following features are noted: A brass plate 6 in. x 1½ in., carries upright bearings on which rests a steel shaft 5¼ in. long and 3/16 in. in diameter. On this slide four brass terminal-holders, 2 in. long, the outer pair of which comprises the external circuit, designed

to pass a current through the mineral, the inner pair the internal circuit which connects with the potentiometer. Where these arms rest on the shaft, they are insulated with celluloid collars, to prevent leakage of current. The opposite ends of the arms carry the needle terminals. The outside pair is of hard-drawn copper wire, 1/16 in. in diameter and ¾ in. long. They incline over most of their length at an angle of 30° to the horizontal, but in the last ¼ in. steepen to 70° and taper to a point, whose area has been computed, when resting on a soft mineral, at roughly

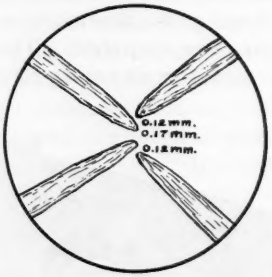


FIG. 2. Appearance of four terminals as viewed through 16 mm. objective.

0.0055 sq. mm. The inner needles, of about the same diameter as the outer, have a cylindrical base of copper 3/16 in. long; the remaining 5/16 in. consists of an alloy of 80 per cent. platinum and 20 per cent. iridium. This alloy portion is of conical form, tapering uniformly to a fine point, whose area when resting on a soft mineral, is calculated to be around 0.00023 sq. mm. The inner needles incline at about 40° to the horizontal. All four needles are held in sockets and are made tight to the arms by means of set-screws. Fig. 2 gives in a general way the appearance of these terminals as viewed through the microscope.

Experiment demonstrated that 0.17 mm. was the most satisfactory figure for the distance between the platinum terminals. Outside of these were placed the copper needles at a distance of

0.12 mm. The total space between copper terminals is then 0.41 mm. This is the minimum size of mineral grain measurable, providing the mineral around the grain under study is a non-conductor.

The electrical current is admitted to the arms by means of binding-posts set close to the point where they rest on the steel

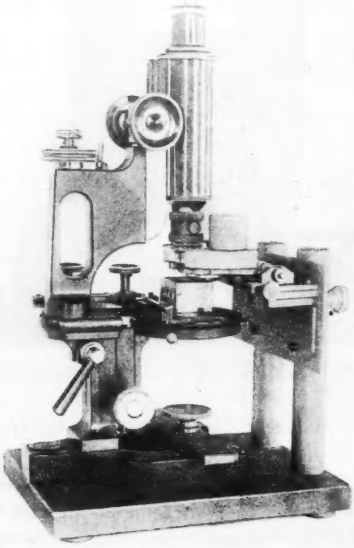


FIG. 3. Microscope and tester in steel frame.

shaft. The arms may be held at any point on the shaft by means of eight collars (provided with set-screws), one on each side of each arm. When not in contact with the polished specimen, the arms may be raised by the hand grip to recline on rubber eccentrics on the long shaft at the front.

All four arms are weighted as shown in Fig. 1. The weight on the terminal of the outer arm averages 160 grams at the tip,

of the inner arm, 7 1/3 grams. Due to the greater area of the former, the pressure computed in pounds per square inch is roughly equal for the two, being in the neighborhood of 15,000 lbs. per sq. in. for a soft mineral and greater for a hard mineral, occasionally reaching 30,000 lbs. In all cases this amount of weight proved sufficient to make good contact.

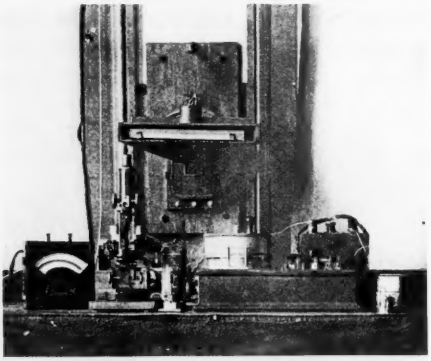


FIG. 4. Tester in circuit with the potentiometer.

Fig. 3 shows the tester clamped to the metal frame. The microscope also is shown clamped to the iron base-plate. In this position it is plain that any point in the specimen is fixed with respect to the terminals, *i.e.*, when the needles are lowered to the polished surface, they maintain that relation as long as desired. No interference is felt from jars of passing trucks.

Electric Circuit of the 4-Terminal Tester.—Fig. 4 shows the tester as above described in circuit with a potentiometer on the inside and a dry-cell and ammeter on the outside. The potentiometer is the delicate type built by Leeds Northrup of Philadelphia. It is superior to the "student's type," but it is believed that the latter would serve equally well. This instrument is capable of reading a potential-fall ranging from 0.00001 to 1.5 volts. The best conductors, the native metals, fall within the

lower reaches of this range, and the writer has found that practically never does a poor conductor cause a fall in potential greater than the upper limit. In case it should or there were some danger that it might, a volt-box, which greatly extends the readable range, may be coupled into the circuit.

The principle of the potentiometer needs no detailed description here. Suffice it to say that by it one reads an unknown potential-fall by "balancing" it against a known, the latter having been previously calibrated by balancing a 2-volt storage-battery against a standard cell. Balance is brought about by varying the E.M.F. in one direction until it equalizes the E.M.F. in the opposite sense, whereupon the needle of a sensitive wall-galvanometer ceases to deflect.

The potentiometer is attached to the binding-posts of the tester, and it is practically the drop in potential between the two platinum terminals that is determined. While there is a slight resistance in the wires leading to the tester, this is almost negligible in comparison with the resistance of the polished mineral, and in any event is constant, so that it may be disregarded.

Current is supplied by dry-cells through the outer pair of terminals of the tester. The writer has found that one cell suffices for the good conductors (most of those in Farnham's first group).[29] For the remaining moderate and poor conductors the number was increased to three dry-cells, yielding an E.M.F. of 4½ volts. Within this circuit is interposed an ammeter (reading to 5 amperes) when an excellent conductor is being studied, and a milliammeter when the mineral conducts poorly. A switch in the circuit obviates the necessity of raising the needle tips to break the circuit.

The reading of the potentiometer expressed in volts divided by the reading of the ammeter expressed in amperes yields the resistance of the 0.17 mm. of polished mineral expressed in ohms. This of course is according to Ohm's law, where

$$R = \frac{I}{E}.$$

[29] *Op. cit.*, p. 123.

It should be understood that the outer terminals need not rest on the mineral whose resistance is being determined, providing the contiguous minerals are conducting. The latter may be either a better or poorer conductor than the studied species. For example, if it is better-conducting than that on which the platinum terminals lie, the ammeter will read higher than if both currents passed through the inner mineral. It will be found, however, that the potentiometer reads higher also, and in fact its reading increases proportionally with the amperage. That is, Ohm's law still holds, and the quotient in ohms is unchanged. Expressed briefly, then, it may be said that the ohm value is unaffected by the resistance of the outer circuit.

For the purpose of determining the effect of exposing a mineral to a relatively high E.M.F., the external circuit was tapped into a 220-volt generator line and by means of a resistance-coil, the current was varied between 0 and 220 volts. All the minerals that seemed to be non-conductors were subjected to high voltages with the results that appear in the Tables I–III.

Elimination of Contact Resistance by the Potentiometer.—The chief value of the potentiometer is that the troublesome factor of contact resistance is eliminated. The ohm-value represents the resistance of the mineral for a certain linear distance (0.17 mm.), not the resistance of that distance combined with a certain value emanating from the contacts of the terminals with the mineral. The cause of this elimination is easily understood, as at the moment of balance by the potentiometer, there is *no passage of current,* and therefore no resistance at any point of the circuit. Resistance is encountered only when there is current-flow.

Technique of Procedure.—The polished mineral, a few minutes before being tested, is burnished, then placed upon the stage, and brought into focus.[30] The potentiometer is newly balanced against the standard cell, and then switched to the 4-terminal circuit. The terminals are lowered into contact with the specimen, a point having been chosen where the mineral under test is

[30] All focusing is done by the stage; thus the microscope tube, once being focused with respect to the needle-terminals, is left untouched.

free from gangue—particularly between the points where the platinum needles will rest, devoid of corrosion marks and abrasive films, and appears fresh and well polished. The switch in the outer circuit is then closed, current being caused to pass through the mineral. Where the nature of the species cannot be guessed at, it is necessary to start with one dry-cell and the ammeter, because, if the mineral conducts easily, so much current will pass that a delicate milliammeter will be temporarily ruined. If insufficient current shows on the ammeter to be readable, two more cells are added and the milliammeter is substituted. The current

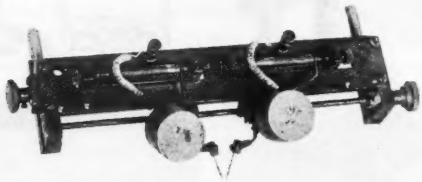


FIG. 5. 2-terminal tester in detail.

being registerable, the potentiometer is as quickly as possible balanced against the unknown resistance. On account of the great variation of the resistance (300 per cent. to 400 per cent., often more) in the same specimen, it is advisable to take several readings at different points, say 3 to 5, and then strike an average as the value for that specimen.

The 2-Terminal Tester.—Figs. 5, 6 and 7 show the 2-terminal tester for use with a Wheatstone-bridge. A brass base-plate, (Fig. 5) 5¾ in. long and 1 in. wide, is slotted to take two adjustable brass bearing-pieces, whose uprights at the extremities carry on jewel (insulating) bearings two steel shafts 1½ in. long (one for each terminal). From the inner end of each shaft extends perpendicularly a brass arm made of 1/8 in. x 1/32 in. material, whose outer terminus is braced by a similar strip attached to the other

end of the shaft. These arms are turned in near their extremity and carry in sockets, provided with set-screws, platinum-iridium terminals, similar to those previously described. The distance between these terminals is variable to a very fine degree by means of the bearing-pieces which ride in the slots. For one the adjustment is coarse, being movable by the hand; for the other the adjustment is fine, being accomplished by a screw at the end.

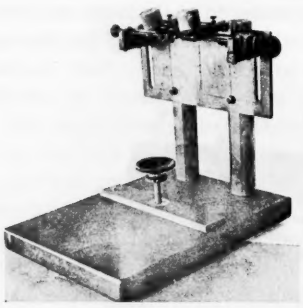


FIG. 6. 2-terminal tester in heavy frame.

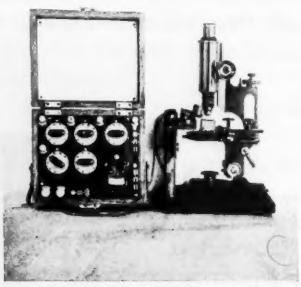


FIG. 7. 2-terminal tester with Wheatstone-bridge.

The standard distance for needle-tips finally adopted is 0.085 mm. At this distance it can be ascertained whether the mineral intervening between the points is homogeneous; there is no interference of the tips, and yet very small grains can be handled.

Copper wires lead off from the arms and attach to binding-posts placed behind the slots on the upper surface of the plate. A device similar to that in the 4-terminal tester is used for raising and lowering the arms. On each arm rides a cylindrical lead weight of approximately 24.5 grams. Computed in pounds per square inch the pressure at the tip of each needle amounts to some 20,000 lbs.

For the measurement of resistance with the 2-terminal tester a Leeds Northrup "S Type" Wheatstone-bridge was used.[31]

[31] In any bridge an unknown resistance is balanced against a known.

This bridge has much to recommend it for the purpose, being portable, light, complete in itself, and possessed of a range that varies from a lower limit of 1/1000 ohm to an upper limit of 10,000,000. (A resistance lying near the extremes is not accurately measurable, however.) The ability to cover this vast range is attributable to the presence of the ratio-arm-box, which multiplies or divides the setting of the resistance-box (in integers from 1 to 1000) by quantities varying from 1/1000 to 1000. As noted, this bridge is complete in itself, and it is only necessary to attach the leads from the tester and close certain switches to make a reading.

Fig. 7 shows the complete circuit including the bridge and the tester mounted before the microscope.

Technique of Operation.—A test on a polished mineral is made more quickly with this circuit than with the potentiometer. The terminals having been lowered to a point on the surface where the mineral is homogeneous and well polished and where the space intervening between the tips is free from foreign grains and pits, the plugs are adjusted on the resistance-box until the needle of the galvanometer shows no deflection.

Failure to Eliminate Contact Resistance by Liquid Media.—During the early period of experimentation an effort was made to do away with contact resistance by interposing conducting liquids between the terminals and the mineral, but it proved unsuccessful. Pure mercury, mercury-sodium amalgam, and several electrolytes (using for the latter an alternating current bridge) were tried. The objections to the use of these liquids may be summarized thus: (1) it is very difficult to induce the mercury to wet the points or mineral, (2) the amalgam wets both, but the difficulty of controlling the size of the drop seemed insuperable, (3) the electrolytes have a high specific resistance, are messy to handle, form discs on the mineral whose dimensions are uncontrollable, and frequently react with the mineral. A slight degree of success was had with NaOH and concentrated HCl, but not sufficient to overbalance the simplicity and speed obtained in using dry contacts.

Summary of Results.—These two types of circuit, potentiometer and Wheatstone-bridge, were used in the study of the large number of specimens comprised in the Murdoch suite, whose identity had been checked by the new microchemical technique of Dr. Short of the U. S. Geological Survey. In addition specimens from many other localities were studied. In all some 2000 separate readings were taken, the results of which appear in the resistance Tables I.–III. beyond.

Below are listed the opaque minerals arranged in families, under each of which appears a description of its electrical behavior as indicated in tests by these instruments, together with notations on the character of certain species.

The native Metals (Table I.).—The potentiometer shows silver, copper, bismuth, arsenic, antimony, and tellurium, (taking the average of the ranges) to have the same order of conductivity as the pure commercial metals. The effect of varying composition is probably shown in copper from nine localities, its total range covering 2400 per cent. The rule that the range of a species extends as the number of localities represented is increased seems to hold for all families.

Arsenides and Antimonides.—These, the second-best conducting groups, all show low resistance. (See Table I.) There is much overlapping, and this will increase with more occurrences. Smaltite cannot be electrically distinguished from chloanthite; nor can dyscrasite from breithauptite. Breithauptite unfortunately also overlaps niccolite.

Tellurides.—This group (Table I.) shows high conductivity, ranking on the average next to the arsenides and antimonides. Whether judged by the potentiometer or the bridge, nagyagite leads the group in resistance. Krennerite appears to have the highest conductivity (potent.).

Selenides (Table I.).—The order of conductivity for four of the commonest species of this group, as determined by the two instruments, checks rather closely. By the potentiometer, the ranges overlap, so that individually they cannot be distinguished electrically, except possibly guanajuatite. On the whole the group ranks next to the tellurides in conductivity.

TABLE 1. RESISTANCE IN OHMS

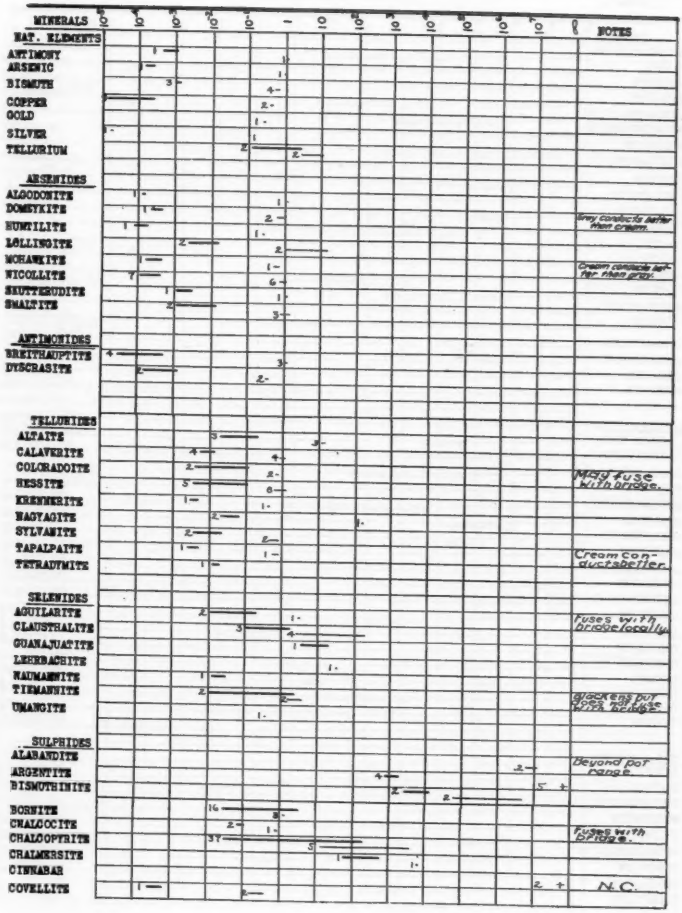


TABLE 2

RESISTANCE IN OHMS

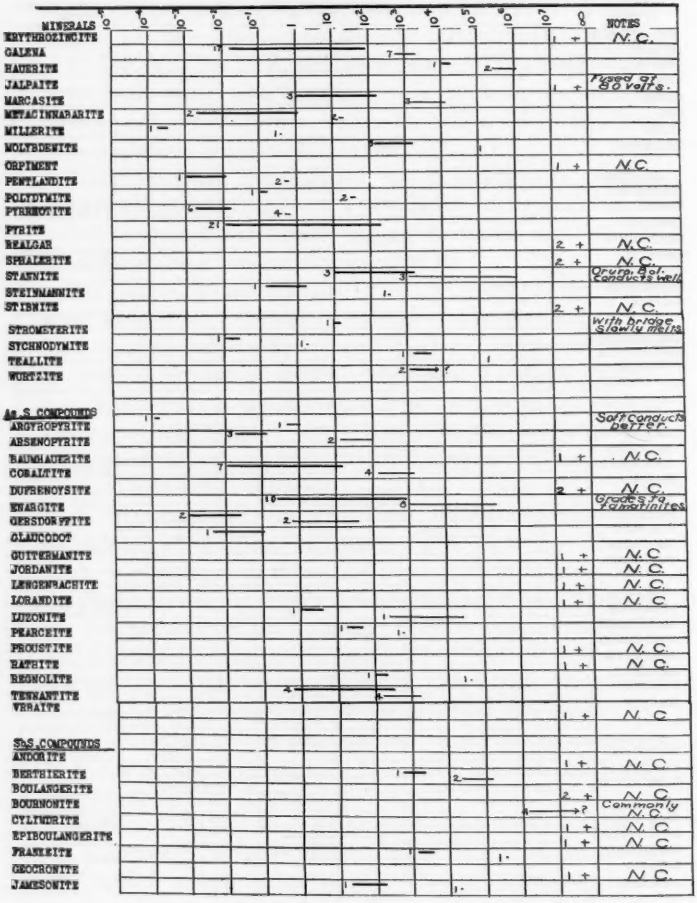
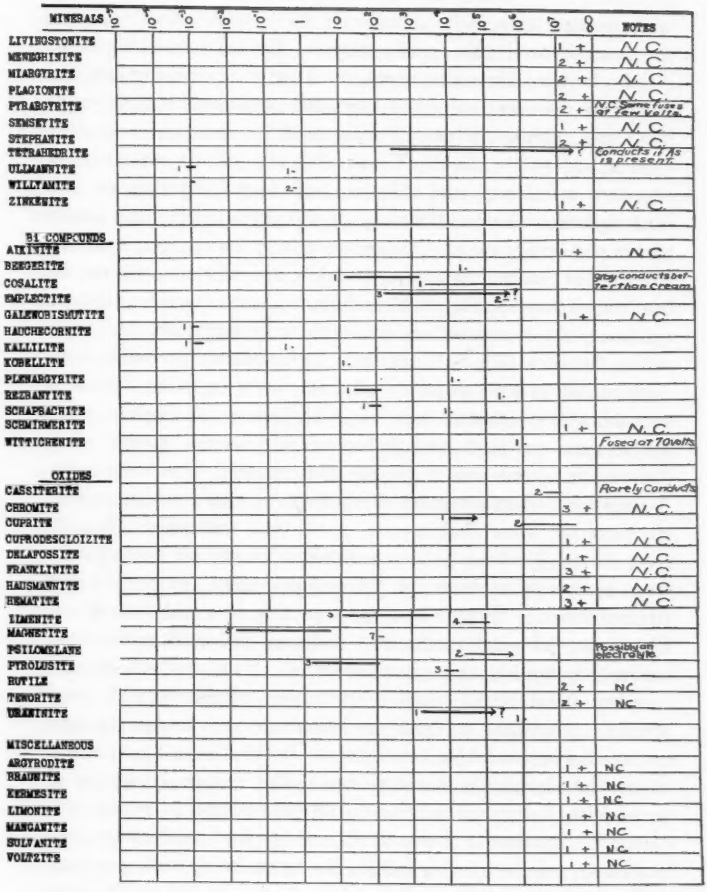


TABLE 3

RESISTANCE IN OHMS



Sulphides (Table I.–II.).—Qualitatively the writer's results for this family check with those of earlier observers (notably, with one exception, Beijerinck). By its electrical behavior before the potentiometer this family may be divided into sub-groups. At the bottom, arranging them in order of increasing conductivity, are the non-conductors: cinnabar, sphalerite, realgar, orpiment and stibnite. None of these could be induced to conduct even at 220 volts. Loewy [32] measured the specific resistance of cinnabar, sphalerite, and stibnite, and found them above 10^8. Such figures are beyond the range of this potentiometer and barely within the bridge range. A second group, including alabandite, hauerite, argentite, bismuthinite, teallite and wurtzite, lies on the borderland between the poor conductors and the non-conductors: specimens from certain localities show no conduction, and ohm-values for these minerals are only the roughest approximations. A third sub-group comprises sulphides with high but distinctly determinable resistances: here are found some chalcopyrite, some pyrite, some marcasite, and perhaps all molybdenite, stannite, and chalmersite; pyrite could not be distinguished from marcasite. A class of moderately good conductors includes bornite, galena, stromeyerite, some chalcopyrite, pyrite and marcasite. Bornite from sixteen localities gave variations of 10,700 per cent., galena from seventeen localities, of 300,000 per cent. In bornite and stromeyerite the current must be kept low to avoid fusion. A fifth group of good conductors, includes chalcocite, metacinnabarite, polydymite, and synchnodymite. Finally, there are the excellent conductors, covellite, millerite, pyrrhotite and pentlandite. According to both potentiometer and bridge the first two are the best sulphide conductors. Pyrrhotite and pentlandite cannot be electrically distinguished. The writer is unable to agree with Beijerinck in classifying pentlandite as a non-conductor.[33] Pyrrhotite shows a remarkably low total range (six localities), compared with galena, the figure being 1680 per cent.

Conductivity tests have, it is believed, definite diagnostic value

[32] Loewy, H., *Ann. d. Phy.*, (4), 36, p. 125, 1911.

[33] Beijerinck, F., *op. cit.*, p. 459.

in the case of chalcocite-covellite, and of chalcopyrite. The potentiometer results indicate that the resistance of rather pure chalcocite is some two hundred times that of covellite (this figure may be diminished as more localities are studied). The conclusion seems justifiable that low-resistance covellite carries low chalcocite, and high-resistance chalcocite low covellite. The potentiometer-resistance of chalcopyrite from thirty-nine localities ranged from that of stannite to that of chalcocite. In comparing the conductivities of these various chalcopyrites with the general mineral association of their respective districts, it was observed that many low-resistance specimens came from mines that contain pyrrhotite, while many high-resistance specimens came from mines that contain bornite. Gilbert has recently commented on the antipathy of bornite and pyrrhotite,[34] and offered possible explanations. The following generalization seems warranted: Of the minerals of a deposit formed more or less contemporaneously from an ore-solution, the two species, bornite and low-resistance chalcopyrite, will not both be found; if one occurs, the other does not. Again, under similar conditions of consanguinity and contemporaneity, pyrrhotite and high-resistance chalcopyrite will not be associated.

Compounds of Arsenic, Sulphur, and One or More Metals (Table II.).—Baumhauerite, jordanite, lengenbachite, guitermannite, lorandite, proustite, rathite, and vrbaite, do not conduct even at high E.M.F. Enargite, luzonite, tennantite, pearceite, and regnolite, are moderate to poor conductors with great ranges. The tennantite-tetrahedrite series (forty-six localities) shows decreasing conductivity with increasing antimony content. Specimens with no arsenic show no or very little conductivity, while true tennantites appear to be moderate or even good conductors.[35] All members of the enargite-famatinite family appear to be conductors. The rule that antimony lowers the conductivity does not appear to hold; on the other hand, all famatinite seems to carry not less than 3 per cent. of arsenic, while tetrahedrite may

[34] Gilbert, G., ECON. GEOL., 20, p. 364, 1925.

[35] This merely confirms an earlier observation of Farnham. *Op. cit.*, p. 123.

show no arsenic. In the case of argyropyrite, arsenopyrite, cobaltite, gersdorffite, and glaucodot, the rule is exemplified that opaque minerals with one atom of sulphur, one of arsenic, antimony, or bismuth, and one of one or more metals, conduct well: this rule appears to be universal. Cobaltite shows a very great range, and is indistinguishable from the other four.

In general it appears that for the compounds of sulphur and one or more metals with arsenic, antimony, or bismuth, the resistance is too great to be measurable by these instruments if the sulphur atoms comprise more than 50 per cent. of the total. For these types of compounds the resistance always seems to increase as the sulphur content increases.

Compounds of Bismuth, Sulphur, and One or More Metals.—Two members of this class (Table III.), hauchecornite and kallilite, exhibit resistances that fall in the third decimal (potent.), while others are non-conductors at high E.M.F. Between these extremes fall the moderately conducting cosalite, emplectite (some is non-conducting), rezbanyite, and schapbachite.

Compounds of Antimony, Sulphur, and One or More Metals.—In general these species (Tables II., III.) are poor or non-conductors, the "one-atom" compounds, ullmannite and willyamite, alone showing high conductivity (but not being electrically distinguishable). Some ten have resistances so high as to be unmeasurable by these instruments. Certain specimens of five or six species exhibit slight conductivity, while other specimens of those species show no conduction at all. Taken as a whole, this group is to be classed as the poorest conductor among the opaque minerals.

Oxides.—Seven of these (Table III.), including chromite, franklinite, hausmannite, rutile and tenorite, are strictly non-conductors. Cuprite lies on the borderland between this subclass and the poor conductors. Some cassiterite falls outside the readable range, other is somewhat conducting (agreeing with Beijerinck). The specimens of hematite examined exhibited high resistance except one in which the ohm-value was readable. The ohm-average for ilmenite appears to lie between those of hematite

and magnetite. Pyrolusite ranks next to magnetite in conductivity; it is by far the most conducting species among the binary compounds of manganese. Psilomelane shows high and variable resistance. Its behavior indicates that it may conduct as an electrolyte, some hydrogen moving to the cathode. A specimen of uraninite conducted at one point, and not at all at two other points. Magnetite, the best of the oxide conductors, showed a variation of 30,800 per cent. from five sources.

Generalizations Based on these Experiments.

In the following summary are noted the major features of agreement between the writer's results and those of earlier investigators, as well as points that are new or little emphasized by the latter.

1. Instruments are described which, by maintaining the area of the terminal tips in contact with the mineral, and the pressure on those tips, constant, tend to produce *constant contact resistance* (which is necessary for the 2-terminal tester and desirable for the outer terminals of the 4-terminal tester). In electrical microscopic examination previously described, this had not been attained.

2. This work confirms the conclusions of previous observers that the conductivity of a natural opaque mineral is not constant. Variations may amount to hundreds of thousands or even millions of per cent.

3. The fluctuations in ohm-value for good-conducting specimens as measured by the potentiometer is commonly around 300 per cent. to 400 per cent. This fluctuation is due to variations in orientation and size of grain. The percentage falls to 200 per cent. to 300 per cent. for the bridge, probably because of the stabilizing effect of contact resistance, which in a well polished specimen tends to approach constancy. As a rule the locality-range (based on all specimens from a district) shows a markedly smaller extent than that for the species (specimens from all localities), indicating, it is believed, a certain degree of chemical control.

4. The earlier conclusion that the poorer conductors show greater variations than the good conductors is confirmed.

5. The cause of these variations is first of all the presence of impurities or inclusions. Other causes are non-uniform temperature, variation in orientation, variation in size of grain, destruction of the crystal-lattice (by heating, grinding, fracturing, oxidation, etc.), and exposure to light. The impurities may be such as are reflected in the departure of a mineral from its chemical formula, but foreign matter not discovered in an ordinary analysis may cause fluctuations out of all proportion to its quantity.

6. This change in the conductivity of a species can in certain cases be connected with known changes in the composition (*e.g.*, chalcocite-covellite, tennantite-tetrahedrite, chalcopyrite). Further work, it is believed, will extend this list.

7. Great as the ranges are in many instances, it is believed that the values for many species will never overlap, and, therefore, such will be electrically distinguishable. A few of these appear below (potent.):

Argentite from native silver,
Chalcocite from covellite,
Gold from chalcopyrite,
Cinnabar from metacinnabarite,
Tennantite from tetrahedrite (no As),
Stromeyerite from stephanite,
Argentite from stromeyerite,
Dyscrasite from all Ag minerals but huntilite,
Molybdenite from graphite,
Bismuthinite from stibnite,
Galena from argentite,
Bismuth from bismuthinite,
Magnetite from hematite,
Pyrolusite from all Mn minerals.

(The majority of these distinctions were noted by earlier observers. Many others could be added to this list.)

8. Of the two instruments the potentiometer excels in that it eliminates contact resistance: on the other hand, the bridge excels in that it can measure a smaller grain, and possesses greater simplicity. The cause of the discrepancy in results by the two instruments are: (1) the presence of contact resistance in one and not the other, (2) differences in temperature produced by unlike amounts of current introduced, (3) failure of the potentiometer terminals to tap a uniform current introduced by the outer electrodes.

9. The writer regards the potentiometer values as the more usable for the excellent and moderate mineral conductors, but the bridge values as the more satisfactory for the poor conductors.

Conclusion.

The writer thanks Professor L. C. Graton for much advice and constructive criticism, and other members of the Departments of Geology and Engineering, Harvard University, for suggestions and the loan of both mineral specimens and electrical instruments.

In a future article the writer hopes to present the results of a study of the dielectric constants of the opaque minerals, using Hatfield's principle of attraction and repulsion.

In the tables above, each equal major vertical column represents an increase in ohm-resistance of 10^1; the columns begin with 10^{-5} and end with 10^7. For each species the bridge value appears below the potentiometer value, or, if only one is present, in that half (of the space devoted to the species) which is proper to it. A number in parentheses before the range indicates the number of localities studied. A single dot shows that only one reading was taken, or that the value for the range is unreliable. NC is for non-conductor. It is regretted that lack of material prevents the list being complete; it is hoped some day to extend it.

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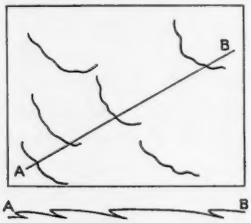
EDITORIAL

A FAULT SURFACE.

SIMPLE as are the general principles that have to be applied in the interpretation of a fault structure, there are so many pitfalls for the unwary that he who has encountered such a one feels inclined to warn others. On the whole, it must be said that observations concerning the details of faults are not published to an extent commensurate with the great importance that these structural features have in economic geology.

In determining the direction of the movement along a certain fault surface, the marks on that surface itself are, under favorable conditions, known to give useful information. The frequently occurring striation shows us the line that the movement has followed, and it is sometimes also possible to tell from the details of the sculpture on the surface the relative directions in which the



blocks on each side of the fault have moved. A well-known and simple rule tells us that this direction can be found by feeling with the hand along the direction of the striae, the surface feeling smooth in the direction that the block represented by the hand has been moving, and more rough in the opposite direction. Höfer, in his book " Die Verwerfungen," points out another sign,

of a similar nature, that is regarded as infallible: the gouge is sometimes rolled out into slightly overlapping tongues ("Rutschlappen") of small dimensions, the edge of each being raised a little—perhaps only a fraction of a millimeter—above the underlying unit.

The writer once encountered a phenomenon that seemed at first glance to be comparable to these "Rutschlappen" of Höfer's, but turned out, upon closer examination, to be something entirely different. The fault plane in question, in the Tuolluvaara iron mine in Swedish Lapland, dips at 60°. A pronounced, large-scale striation runs obliquely across it, making in the fault plane an angle of about 20° with the horizontal. In several exposures, the fault surface is found to be scaly, in the way shown somewhat schematically in the accompanying sketch, in approximately one fifteenth of the actual dimensions (in the section, the vertical scale is exaggerated). This feature may be described as a tendency in the rock to spall off in the form of overlapping broad tongues, the axes of which roughly coincide with the direction of the striae. The rock in question is a slightly metamorphic, very fine-grained quartz-syenite-porphyry, without any schistosity, and with irregular jointing.

A general study of the geology of the mine showed that the movement along this fault could not possibly have taken place in the direction that would in this case be indicated by the rule of the "smooth or rough" direction, but vice versa. It is clear that this must not be regarded as an exception to Höfer's rule of the "Rutschlappen," for the phenomenon at the Tuolluvaara fault is something different, being located in the hard rock itself and not in the plastic gouge. The most probable explanation seems to be that the imbricate structure was formed by strains set up in the rock when movement was in progress along the fault. The direction thus indicated shows that the fault had the character of an overthrust, as also seemed most probable from the oblique movement.

PER GEIJER.

DISCUSSION AND INFORMAL COMMUNICATIONS

THE ORIGIN OF CORUNDUM APLITE.

Sir: In the June–July number of Economic Geology Doctor E. S. Larsen has very thoroughly reviewed recent investigations upon the genesis of corundum in aplitic bodies and has pronounced in favor of a hydrothermal origin in preference to the theory of the desilication of an acid magma more or less *in situ.*

It is necessary to scrutinize carefully his arguments, making particular appeal to the deposits in South Africa to which this theory was first applied in 1918, though, from the available descriptions, the several occurrences in the United States and elsewhere would appear to be remarkably similar.

In some ways the question concerns the precise conditions of pegmatite intrusion and, when such have been more clearly defined, it may be found that the author's viewpoint is not quite so far removed from that hitherto advocated. Suggestive is a remark of his (p. 427) that the desilication theory "would require a radical revision of our ideas as to the character of pegmatite magmas and the conditions under which they crystallize." It is generally admitted that at one extreme stand the purely igneous intrusions, at the other the aqueous vein formations, and in common with most petrologists I have regarded aplites and pegmatites as fairly high- or moderate-temperature offshoots from an acid reservoir, within which a certain proportion of mineralizers has been concentrated. Under these circumstances the experiments by Morozewicz are not believed to have too much bearing on the crystallization of corundum in aplitic rocks.

The influence of an invaded formation upon the character of a granite-aplite or pegmatite is perhaps insufficiently appreciated. In the sial-seamed pre-Cambrian complex of South Africa it can be observed that in ortho-gneisses and acid granulites, such veins

appear usually as quartz-microcline pegmatites, in hornblende-gneisses and amphibolites as feldspar-aplites often carrying hornblende, and in garnetiferous schists and amphibolites as feldspar-aplites with hornblende and garnet. Their study shows that reactions have taken place between the acid magma and the walls, which have in certain cases led to decided changes in the chemical composition of the intrusive magma as well as of the invaded formation.

While the field evidence, admirably marshalled by Doctor Larsen, would seem to point overwhelmingly in favor of mutual reaction between the aplitic bodies and their ultrabasic walls, and thus support the theory of desilication, he seems to have found his main difficulty in reconciling such a genesis with the limited breadths of the marginal contact zones when compared with the widths of the aplitic bodies. The justness of such a view must be admitted, could one accept the calculations submitted as to the amount of material that would have to pass out from a dike into the country rock, but the rather idealized balance sheet presented by him is not above criticism. He assumes first an original granitic magma with 75 per cent. of silica, high potash and no lime, and on the basis of the soda-content, deduces that at least one half would have to diffuse into the border zone in order to leave behind a material that would crystallize as plumasite. Now, as pointed out in my original paper (p. 58),[1] the abundant veins in the hornblende-granulite complex surrounding the Natal serpentine bodies are predominantly feldspar-aplites—*i.e.*, quartz-poor rocks—while they have a lower potash content than that assumed and contain lime in the form of plagioclase. Apparently they have lost some of their original silica to the enclosing granulites, but that is another story. On the other hand, the corundum-aplites always contain lime and the marundites, potash in the form of orthoclase, so that the contrast between the composition of the parent magma and that of the desilicated product is much less than as presented by the author. Furthermore the composition of the talc-phlogopite zone, developed by the migration of silica, potash

[1] Du Toit, A. L., "Plumasite (corundum aplite) and Titaniferous Magnetite Rocks from Natal," *Geol. Soc. So. Africa, Trans.*, 21, 53–73, 1918.

and fluorine into the serpentine, suggests some passage of lime and alumina from the country rock into the invading dike.

The total loss of material from the aplite in its reduction to plumasite is in this case distinctly less than that computed by Doctor Larsen, and indeed becomes more closely comparable with that to be deduced from the magnitudes of the reaction borders observed in the field, widths on either side greater than the breadth of the plumasite bodies having frequently been measured. It should not be overlooked that the dikes described as plumasite or marundite are not homogeneous rocks everywhere carrying corundum to the extent of from 20 to 50 per cent., but may in places pass into a nearly pure albitite. The corundum is largely concentrated within certain zones or pockets and specially within the apices of the veins, that is to say pre-eminently in those parts of the magma placed longest or most effectively in contact with the ultrabasic rock; further elaboration is hardly necessary. It is improbable that transfusion began only *after* the magma had attained its final resting place, while it is obvious that a certain amount of movement and differentiation occurred during consolidation. One is therefore led to doubt as to how far it becomes feasible to deal with such a complex problem on a strictly quantitative basis.

On the other hand, the many recorded cases of these aplites carrying a certain amount of quartz, but possessing quartz-free feldspathic zones or containing bands or patches with corundum that approach plumasite or marundite in composition, are to be interpreted as truly siliceous aplites in which the desilication has been incomplete. Such examples are particularly illuminating in revealing the intermediate stages of that process; in Natal they are not common, but Hall has given in detail many instances from the Transvaal.

In dealing with the Natal occurrences the rôle played by mineralizers, indicated by the presence of fluorine and boron and by the conversion of corundum into margarite, was not overlooked, though the pneumatolytic aspect was fully discussed by Hall in describing the extensive deposits of the Transvaal. Although the

evidence would ascribe the source of such solutions to the magma itself rather than to the ultra-basic rocks, as suggested by Larsen (p. 431), I have pointed out that the conversion of the serpentine into talc through the introduction of silica would set free a small amount of water. Such may perhaps have been a factor of importance during consolidation. All the data, however, substantiate the view that these aplites are veins arising from the subjacent granite, identical in their origin with those that permeate the gneisses, granulites and basic schists associated with the ultrabasic rocks. The hydrothermal theory involves us on the contrary in far greater difficulties, as for example the question of the source of such solutions, their unique aluminous character, and their crystallization selectively in ultrabasic formations; it certainly does not seem adequate to explain the passage of a quartz-pegmatite into a plumasite.

In conclusion, it is submitted that the evidence accumulated so far supports to the full the theory of desilication, the bodies being regarded in conformity with current views as largely "igneo-aqueous" melts, but that pneumatolysis may sometimes have accompanied, and certainly often followed, their consolidation, as is particularly marked in the case of the important group of the corundum-margarite aplites or marundites.

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CARBON RATIOS AS AN INDEX OF OIL AND GAS.

Sir: In the issue of ECONOMIC GEOLOGY for June–July, 1928, there appears an extremely important contribution by I. W. Jones on "Carbon Ratios as an Index of Oil and Gas in Western Canada."

I venture to think that the brilliant theory of D. White has been accepted with too little criticism, and I know from experience, that such acceptance has led to unrewarded hopes and expectations. In a matter of such far-reaching importance as this, a theory should not be regarded as proven until the statistics of

the whole world have been collected and analyzed. I am well aware that the protagonists of the theory have covered a vast amount of ground in the collection of their facts. I venture, however, to draw attention to one very important contribution, which, by reason of its medium of publication, has been overlooked. I refer to a masterly discussion on the subject of carbon-ratios of coals in relation to gas and oil, by Dr. Arthur Wade in "Petroleum: Report on Investigations made in New South Wales," published as a Parliamentary Paper of the Commonwealth of Australia in 1925.

In this report, Dr. Wade deals exhaustively with the carbon ratios of the coals of Permo-Carboniferous age in the great Hunter River coalfield of New South Wales. He shows that the carbon ratios of the Lower or Greta Coal Measures are lower than those of the Upper or Newcastle Measure, although the latter are at least 8,000 feet higher in the sequence. His conclusion is the same as that reached by other opponents of the carbon-ratio theory, namely, that the carbon ratio is affected by the nature of the coal, which, in turn, depends upon differences in the ultimate material from which the coal has been derived, and in the conditions under which such material has been accumulated and preserved.

His summary is a masterly one, and it seems a pity that it should not be better known. Copies of the publication in question can be obtained on application to this Department at a cost of one shilling and six pence.

W. G. WOOLNOUGH.

COMMONWEALTH OF AUSTRALIA,
HOME AND TERRITORIES DEPT.,
CANBERRA, F. C. T.

REVIEWS

Eruptive Rocks, Their Genesis, Composition, Classification, and Their Relation to Ore-Deposits. By S. J. SHAND. Pp. xx + 360. Illus. 44. London, Thos. Murby and Co., 1927. Price, 20 s.

The purpose of the author in presenting his book to the public was threefold: first, to "clean up the jungle of rock names"; second, to make the conclusions of petrological study intelligible to physicists and chemists, who think in quantitative terms and are apt to listen with indifference to assertions of 'affinity' and 'consanguinity'; and third, "to bring theory and practice together"—to "show that the miner and the petrologist have need of each other's help." In the matter of terminology and nomenclature the author has "gone his own way, guided by the general principles that names should be as few as possible, that the simplest terms are the best, and that when an English term can be used without obscurity, it should be preferred to a Latin or Greek one."

The author discusses in a critical manner the underlying principles of petrology and offers numerous comments as to their significance. Some of these indicate a better appreciation of the logical deductions from the facts observed than is commonly held, whereas, on the other hand, other comments suggest merely the dressing of the usual deductions in a new set of terms.

In the first chapter, after critically examining the grounds for concluding that lavas and granitic rocks are alike the products of magmas he suggests that, in order to emphasize the differences in the earlier and later phases of magmatic cooling, we adopt "a convention to the effect that all crystalline rock masses and veins which contain much quartz of prismatic or fibrous habit, and little or no felspar, shall be excluded from the category of eruptive rocks."

The next two chapters deal with the fixed and fugitive constituents of magmas, and the influence of the fugitive components upon the physical properties of the magma. The fourth chapter treats of the character of magmas, their temperatures and their effects on inclusions, and the fifth chapter of the process and order of magmatic crystallization, including a discussion of the incompatability between components that are saturated and those that are unsaturated with respect to silica. The last two chapters deal with meteorites and eruptive ore deposits.

The main portion of the volume treats of the classification of eruptive rocks, which is gone into in great detail. In brief, the proposed major

divisions are into rocks that are oversaturated with silica, including granites, rhyolites, tonalites and dacites, those that are saturated, including syenites, shonkinites, diorites, gabbros, perknites and their effusive equivalents, and those that are undersaturated. The undersaturated rocks are subdivided into feldspathoidal and non-feldspathoidal types. The feldspathoidal types are those containing feldspars and leucite, or some soda feldspathoid, and the non-feldspathoidal types include those composed of feldspars and unsaturated aluminous, magnesian, and lime minerals, such as corundum, olivine, melitite, etc. Each major group is further divided into subgroups on the basis of their content of alumina, which may be present to oversaturation, saturation or undersaturation as compared with soda, potash and lime, and these subgroups are further subdivided in accordance with the ratio of light to heavy minerals in the rock, or essentially the ratio of pale-colored to dark-colored minerals. When applied practically the author's classification is not very different in principle from the American quantitative system, except that it emphasizes the mineralogical rather than the chemical character of the rocks classified.

It is impossible in this place to discuss in detail the new classification proposed by the author, or to call attention to the new names that he finds it necessary to use for many of his groups, since this would require more space than is available, and, moreover, no just notion of the thoroughness of the author's treatment of the subject could be given in any abstract. The student would, in any event, be compelled to read the book in order to gain a proper view of its philosophy.

It must suffice to state that the volume is full of suggestive thought, and that the conclusions are worthy of careful consideration. There is in its pages a great wealth of information concerning rocks from all over the world and a fund of chemical data that is of value to any serious student of rocks. Nearly all rocks that have been given distinctive names are briefly described and are fitted into the classification, and to each chapter is appended an excellent bibliography.

In short the volume is a compendium of petrographic information which should be read with care by everyone interested in petrology. Its excellent bibliographies should be of great value to the student as a guide through the maze of petrological philosophy.

The treatment of eruptive ore deposits is rather brief, but since many of the processes that have to do with their deposition are dealt with in connection with the discussion of the solidification of rock magmas, it is sufficiently full for the author's purpose, which is mainly to show that "The eruptive rocks and the eruptive ore-deposits form a continuous series in which the temperature of formation falls steadily from that end to this, while the water content (or more generally the content of fugitive substances) of the magma solution rises in the same direction."

The eruptive ore deposits are divided into six classes as follows: (1) Primary disseminations, (2) Primary segregations, (3) Contact deposits, (4) Self-replacements along pipes and fissures—the pneumatolic deposits of some writers, (5) Pegmatite and aplite veins, and (6) Quartz veins. Groups 3 and 4, and 5 and 6 grade into one another. The principal value of this portion of the volume lies in the many occurrences cited to illustrate the different classes and the excellency of the brief bibliography furnished.

The book is well worth a careful reading, not only by petrographers but also by the students of ore-deposits.

W. S. Bayley.

The Geology of Petroleum and Natural Gas. By Ernest Raymond Lilley. 503 pages, 173 illus. D. Van Nostrand Co., Inc., New York, 1928. Price $6.00.

This work is intended to supply professional petroleum geologists "with a single volume in which they may find brief statements of principles of the science and examples illustrative of the application of those principles. It is further hoped that the student who is preparing to enter this field of work will find in it an adequate statement of the principles that he is studying." The reviewer will consider the latter group of prospective readers only, since he considers that the commercial geologist must perforce be far in advance of any such text. He feels also that no textbook can present the science adequately to two such diverse groups.

The text is devoted almost entirely to structure. Of its 503 pages, only 44 deal with "Geological History and the Occurrence of Oil." In the chapter on "Exploration of New Areas" the discussion is based almost entirely on surface indications and structure. The word 'paleogeography' does not appear in the index nor is there any real discussion of this phase of the subject in the text. Stratigraphic sections are given in profusion with little suggestion as to their preparation or use.

The book may be divided into three parts: the first four chapters deal with the properties and origin of petroleum, the next five with general principles of the occurrence of petroleum and the remaining nine with descriptions of fields grouped according to structural relations.

In the first part very much the same ground is covered that is taken up under the head of the National Hydrocarbons in Clarke's "Data of Geochemistry." The author sets up all the straw men of the upholders of the theory of the inorganic origin of petroleum and knocks them down again just as so many others have done. In fact in the first part of Chapter IV., "The Origin of Petroleum and Allied Substances," 45 references are cited of which 35 can be found in the "Data of Geochemistry." Had this section been greatly reduced and had much of the 88

pages it takes up been devoted to oil geology the book would be of greater value.

Considering it in greater detail we find (p. 17) a complete description of both the Baumé and the A. P. I. scales. Since the latter has been adopted by both the oil industry and the Bureau of Standards, the former might well have been omitted and the frequent references to the Baumé scale converted to the one now in general use.

In the chapter on "Mineral Bitumens related to Petroleum" the anthraxolite of the Sudbury district and the Siberian tschungite should have been added, especially because of their association with metamorphosed Pre-Cambrian rocks.

The reviewer was surprised to learn of the association of oil with thermal or magmatic waters in Trinidad (p. 58) and particularly surprised to find that the magmatic origin of these waters is of such common acceptance that no reference is necessary.

In discussing the presence of sulphur in oils reference is made to the views of Emmons regarding the action of sulphate-reducing bacteria (p. 83) but Bastin's work is not mentioned.

In the second part of the volume the chapter on "Geologic History and the Occurrence of Oil" leaves a great deal unsaid, as must any chapter dealing with such a topic in less than 50 pages. Much more space could easily have been devoted to this phase of the subject, particularly to the correlation of formations, to a discussion of the diastrophic record and to transgressions and regressions of the sea. These are considered in a general way but not in sufficient detail to be of value to the oil geologist. Nor does the bibliography at the end of the chapter help greatly, since neither the company geologist nor the student will get a great deal from textbooks on historical geology, yet out of nine references in the bibliography six are to such books. In this chapter no mention is made of the work of Ulrich. Schuchert is represented by three paleographic maps. No mention is made of the Devonian limestone production of Kentucky and Ontario. The older producing horizons in Trinidad are considered Cretaceous in spite of the work of Waring who placed them definitely in the Tertiary.

In the chapter on reservoir rocks the reviewer noted with interest that "unlike the perfect soil the grains of sedimentary deposits are of varying shape" (p. 162) and that "in considering the shape of particles it is necessary to make allowance for their internal structure"—this latter in a discussion of pebbles—and (p. 173) that "while sands and sandstones are productive of oil in practically all of the important fields of the world, limestones are unknown as producers in many and are important in only a few." This last statement, it is pleasing to note, is not borne out by the treatment the author accords to limestone fields elsewhere in the book.

The next chapters on the "Concentration of Oil and Gas" and on the

"Representation of Structural Conditions" are well written, although the reviewer wishes that the differences between driller's logs and interpreted logs had been stressed a little more. Structure contour maps and sections always look so simple and straightforward that it would seem necessary to warn the student that they are not so simple as they appear.

The third and most important part of the book is presented much more clearly than the other parts. In the first place, the author gives examples of fields in more or less increasing order of complexity, thus doing away very largely with the "here's another" method employed in most textbooks on economic geology. He does not cling to the purely artificial subdivision of fields into Mid-Continent or Rocky Mountain, nor does he overemphasize the fields east of the Mississippi River.

There are two indices, the first an author index and the second a subject index. In the former there seems to be no need of omitting the second initial of every author's name. One has become so used to T. C. Chamberlin, K. C. Heald, or K. F. Mather, that to see them referred to as T. Chamberlin, K. Heald and K. Mather comes as a bit of a shock. A third or stratigraphic index would be of great assistance especially since the author has not paid any attention to location in arranging his discussion of the various fields. Thus if one wishes to find rapidly what fields produce from the Wilcox sand it is necessary to run through several chapters to do it.

In spite of many imperfections the book is extremely valuable. The author has frequently departed from the traditional way of handling the subject with excellent results. The reviewer is particularly pleased to note that the idea that a porosity of 12.3 per cent. may be produced by dolomitization is rather scouted and that limestone reservoirs come into their own to a greater extent than in any other book that he has read. The volume deserves a place, and a prominent place, in the library of everyone interested in oil geology, and it is to be hoped that in the second edition the author will depart even more from tradition and omit much of the discussion of the nature and origin of petroleum and tell us more about its stratigraphic and paleogeographic relations.

There appear to be few typographical errors. On page 293 two page references are omitted, on pages 313 and 315 the compositor headed the pages with the heading of the previous chapter, and on page 400 Hercynian is spelled 'Heroynian.' M. I. Goldman is referred to as M. A. Goldman on Page 106. There are 173 figures, most of which are very well chosen subsurface maps or sections, and 62 tables, of which most are stratigraphic sections of individual fields or areas.

W. V. Howard.

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Urbana, Illinois.

The Undeveloped Mineral Resources of the South. By H. M. PAYNE. American Mining Congress, Washington, D. C. Pp. 368, 8vo, 1928.

This is a compilation of previously scattered information that will be welcomed by those interested in the general distribution of the mineral resources of the Southern States.

"The book is not offered as a strictly technical or geological work; but rather as a commercially convenient compilation of the mineral resources of the South, designed to afford the student, the consumer, the investor, and the producer a ready source of information regarding the nature and the extent of these minerals; how they may be identified; where additional supplies have been proven up, or areas whose surface indications warrant further prospecting; what economic factors have speeded, retarded or prevented their development; and new avenues of outlet for the product."

The book is divided into twenty-five chapters, and in each are discussed minerals with somewhat similar characteristics, modes of occurrence and uses. A final chapter is added which gives an extensive bibliography. Under the heading of each chapter each southern state is treated separately. The locations given are quite general, usually the county, but to have given more would have enlarged the volume beyond convenient size.

This volume should be a welcome addition to the working library of any one interested in the development of the South. The South has already awakened to its great industrial advantages, but has been very slow to recognize its mineral possibilities, and the reviewer believes that the American Mining Congress has rendered a great service to the South in focusing attention on these possibilities. So far as the reviewer is aware, the volume is presented gratis to those primarily interested in industrial development in the South.

R. S. POOR.

BIRMINGHAM-SOUTHERN COLLEGE,
BIRMINGHAM, ALABAMA.

Elements of Optical Mineralogy, an Introduction to Microscopic Mineralogy. By ALEXANDER N. WINCHELL. Third Edition. Pt. I. Principles and Methods. Pp. 238. Ills. 260. John Wiley & Sons, New York. 1928. Price $3.50.

The third edition of this popular treatise on optical mineralogy differs little from the second edition, except in the addition of a chapter describing the use of the universal stage in the determination of the indices of refraction and other optical properties of minerals in thin sections and in grains. These new methods, which are discussed in the text, offer a rapid and accurate means of determining several indices of refraction of a single particle without the necessity of changing immersion liquids, thus

supplying the data from which its other optical constants may be calculated. It might be better for the student who is not already familiar with the manipulation of optical instruments if the "directions for laboratory work" were made more explicit.

It is probably unnecessary to state that the book is the most satisfactory English text on optical mineralogy now available.

W. S. BAYLEY.

Oil and Gas Development and Possibilities in East-Central Illinois. By L. A MYLIUS. Illinois State Geological Survey, Bulletin No. 54, 1927; 205 pp., XXXI. plates, 13 figs.

This bulletin maintains the excellent standards set by the Illinois State Geological Survey in its reports of investigations of oil fields within the State, and gives a detailed account of the stratigraphic, structural and historical geology of the Clark County fields and the area adjoining these fields to the north and northwest. In addition there is a detailed description of the individual pools.

For the student of oil geology, however, the report contains much more than the usual descriptive matter. Problems of operation and production supplement the usual text on oil geology. The numerous maps and sections are accompanied by notes on the use of logs, cuttings and cores and show how the maps and sections are prepared. Finally the more important log and drilling data are given for more than 5,000 wells and dry holes in the Clark County field. This mass of data provides excellent material for use in problems given in connection with courses in oil geology. It includes the location of wells, elevation, depth and thickness of all pays, depth of best pay, initial production, total depth, and remarks concerning production—including in many cases the location of water sands. It is evident that such material can be used to advantage in teaching, and in its completeness it affords opportunities for detailed work which can be found in only a very few areas.

No student or teacher of oil geology can afford to be without this report, and it may well present facts and suggestions of great value to geologists engaged in the development of oil fields elsewhere.

W. V. HOWARD.

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BOOKS RECEIVED.

Geology and Mineral Resources of the Herscher Quadrangle. By L. F ATHY. Pp. 120, figs. 38, pl. 2. Ill. State Geol. Surv. Bull. 55, 1928 (Sept.).

General geology; stratigraphy; glaciation; coals, gravels, clays.

The Falls of Niagara. By GLENN C. FORRESTER. Pp. 154, illus. 42. D. Van Nostrand Co., New York, 1928. Price, $2.50.

A good, dependable geologic story of Niagara, popularly written.

The Geology of British Honduras. By LESLIE H. OWER. 24 pp.; map. Bolize, 1928 (July). For sale by Colonial Secretary, Bolize. Price, 25 cts.

Summary of geology, with a geological and topographical map, scale 1:1,000,000. The possibilities of locating tin, gold, and petroleum are discussed.

Anthracite Culm and Silt. By J. D. SISLER, T. FRASER, and D. C. ASHMEAD. Pp. 268, pl. 32, figs. 21. Penn. Geol Surv. Bull. M 12, 1928 (Sept.).

Production, disposal, uses, recovery, sampling, of fine coal sizes.

Geology and Lignite Resources of the Marmarth Field, Southwestern North Dakota. By C. J. HARES. Pp 110, pl. 6, maps 8. U. S. Geol Surv. Bull. 775, 1928 (Sept.).

General geology, stratigraphy, structure, and lignites.

Bituminous Coal Fields of Pennsylvania, Part I, General Information on Coal. By GEORGE H. ASHLEY. Pp. 241, figs. 32, pl. 17. Penn. Topogr. and Geol. Survey, Bull. M-6, 1928 (Oct.).

A valuable book authoritatively written, giving the physical and chemical properties, origin, classification, and classes, of coals. Brief descriptions of Pennsylvania coal beds and series, mining and uses.

Ground Water in the New Haven Area, Connecticut. By J. S. BROWN. Pp. 206, figs. 19. U. S. Geol. Surv. Water Supply Paper 540, 1928 (Oct.).

Geology, physiography, ground water and detailed descriptions.

Surface Water Supply of the United States, 1924. Part I, North Atlantic Slope Drainage Basins. 246 pp. U. S. Geol. Surv. Water Supply Paper 581, 1928 (Oct.).

Coal Resources of the Union of South Africa, Vol. III. By W. J. WYBERGH. Pp. 181; 15 maps. Union of South Africa, Geol. Surv. Mem. 19, 1928 (Oct.). Price, 10 s.

The final volume on this subject, treating of the coalfields of Eastern and Southeastern Transvaal and Cape Province.

SCIENTIFIC NOTES AND NEWS

Wilbur A. Nelson has resigned as State Geologist of Virginia, and will devote his entire time to his official duties as head of the School of Geology at the University of Virginia.

L. H. Warwick, previously chief clerk, is now acting head of the Virginia Geological Survey.

Per Geijer has just arrived in Chile and will return to Sweden about Christmas time.

G. F. Loughlin, of the U. S. Geological Survey, visited Cripple Creek and Bonanza districts, Colorado, before returning to Washington.

Charles P. Berkey was the principal speaker at the Colorado School of Mines on Engineers' Day, October 26.

W. Spencer Hutchinson has gone to Chile.

F. E. Matthes, of the U. S. Geological Survey, is making a study of the geologic history of the Mississippi River and its tributary system in connection with plans for flood control.

Arthur B. Parsons, formerly associate editor of the Engineering and Mining Journal, is now vice-president of the Mineral Research Corporation, 120 Broadway, New York City.

J. S. DeLury, of Saskatoon, Saskatchewan, has succeeded R. C. Wallace as Commissioner of Mines for Manitoba and professor of geology and mineralogy at the University of Manitoba.

B. S. Butler, of the U. S. Geological Survey, recently finished his work in the Alma mining district of Colorado and returned to Tucson, Arizona, where he is connected with the State University.

H. H. Knox, former president of the Mining and Metallurgical Society of America, is now in Queensland, at the Mount Isa Mines.

H. G. Ferguson, of the U. S. Geological Survey, has been studying the conditions in the Allegheny district in California.

H. G. Schneider is now chief geologist of the Dixie Oil Company, with offices in the Slattery Building, Shreveport, La.

M. J. Elsing, mining engineer, formerly of Bisbee, Arizona, is now located at Tucson.

George H. Garrey, after making a geological examination of the Tin Cup mining district, Gunnison, Co., Col., has gone to Maricopa Co., Arizona.

Sydney H. Ball recently made a trip to Colorado.

Charles W. Wright left this country in September for a trip to Italy.

J. S. Ross, of the U. S. Bureau of Mines, has been transferred from Midwest, Wyoming, to Shreveport, Louisiana, to take charge of a temporary station and make a study of the Trinity formation at Cotton Valley.

Olaf P. Jenkins has returned to New York after three years spent in geological exploration in the Dutch East Indies.

L. M. McNaughton has left the Humble Oil and Refining Company, East Texas, and is geologist of the Rycade Oil Corporation at Houston.

E. E. Campbell, of Toronto, was lately in Kingman, Arizona, inspecting the properties of the Old Colony Mines.

J. A. Bancroft has resigned his position as Dawson professor of geology at McGill University, Montreal, and is engaged in surveying work at Broken Hill, Northern Rhodesia.

Frank Ayer, manager of the Morenci branch of the Phelps Dodge Corporation, is in charge of work at Tyrone, N. M., where about 12,000,000 tons of low-grade ore has been developed by the company.

Howard E. Simpson, professor of geology at the University of North Dakota and State Water Geologist, has returned to Grand Forks after a year of absence, during which he made many ground water surveys for new or improved water supplies throughout the Northwest.

Samuel Richardson, mining engineer, has become assistant manager of the Jack Waite Consolidated, in the Coeur d'Alene district.

Leon Gabriel is manager of the South American Manganese Company, an English company for the development of properties in Minas Geraes, Brazil.

The Annotated Bibliography of Economic Geology has had the minimum sum of $18,000 subscribed and underwritten, and the work for 1928 is now under way. This has been made possible, however, only by the guaranty of $3,000 by a friend of the project. It is therefore necessary to solicit further subscriptions until the minimum sum has been reached.

International Geological Congress. In addition to the various steamship concessions granted to members of the Congress as announced in the recently issued "Supplement to the Second Circular," the Organizing Committee have now been advised that the American South African Line has agreed to grant a rebate of 15 per cent. to members attending the Congress in South Africa.